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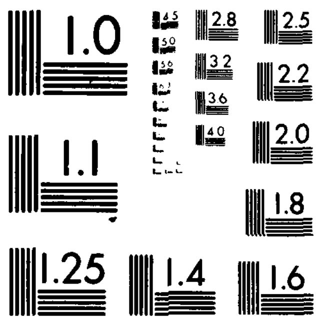

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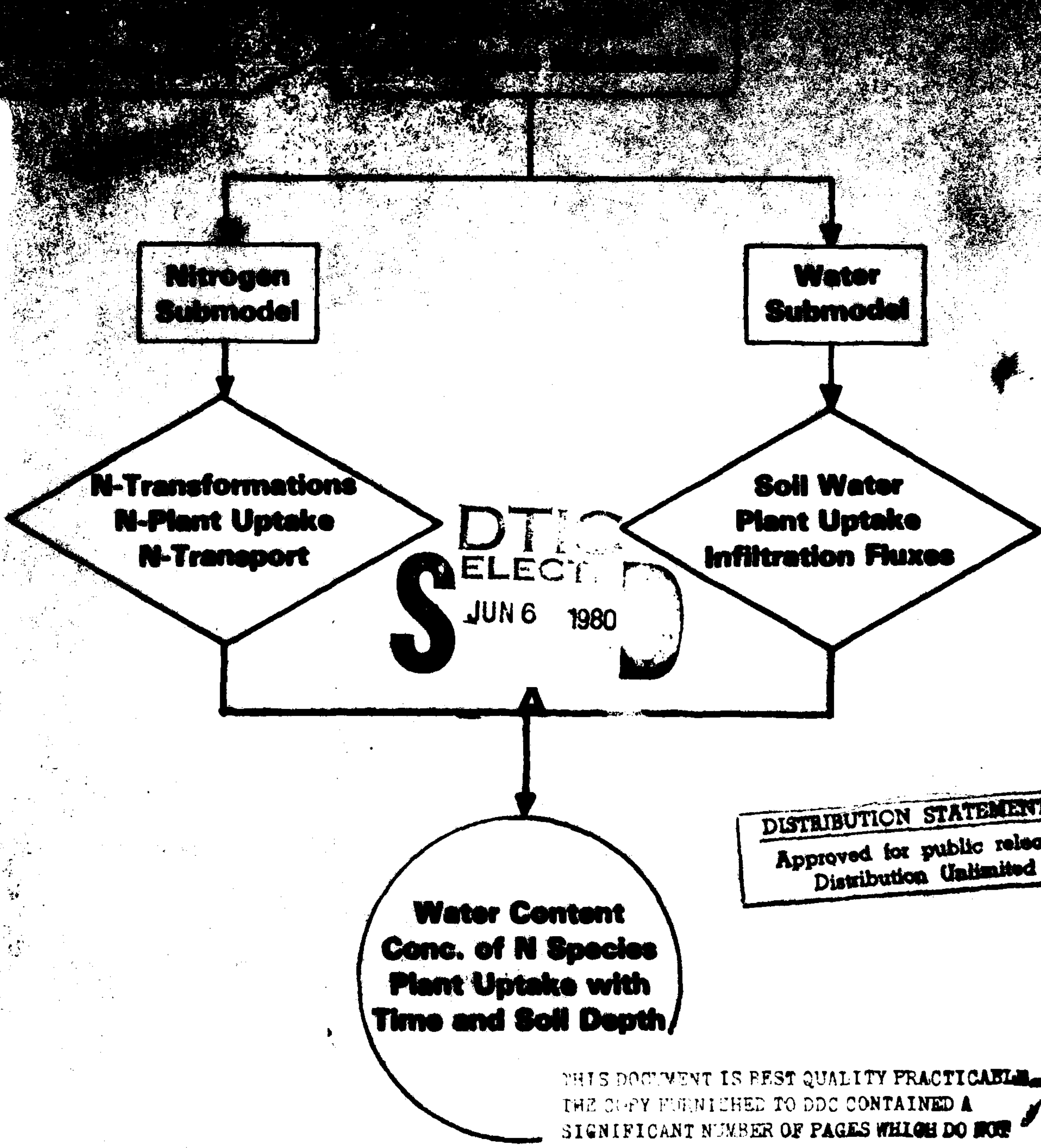

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Simplified model for prediction of nitrogen behavior in land treatment of wastewater

H.M. Selim and I.K. Iskandar

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A simplified model for simulation of nitrogen transformations and transport in land treatment of wastewater is presented. The purpose of the model is to predict the behavior of NH_4^+-N and NO_3^--N in the soil profile in land treatment systems. The program is based on the solution of the transient soil water flow equation simultaneously with the equations describing the transformation, transport, and plant uptake of nitrogen in the soil. The program is valid for uniform as well as multilayered soil profiles and can be adapted to incorporate various nitrogen transformation mechanisms and boundary conditions. The model can be used as a tool to predict the fate of nitrogen in land treatment systems. Model sensitivity to changes in the rate of nitrification, ammonium ion exchange, and rate of plant uptake of nitrogen is also described. Description of the computer program, the program listing, and an example of input data and a two-week computer simulation of output data are presented.

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PREFACE

This report was prepared by Dr. H.M. Selim, Assistant Professor, Department of Agronomy, Louisiana State University, Baton Rouge, Louisiana, and Dr. I.K. Iskandar, Research Chemist, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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This report was technically reviewed by Dr. R.S. Mansell of the University of Florida and Dr. M. Mehran of the University of California-Davis.

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SIMPLIFIED MODEL FOR PREDICTION OF NITROGEN BEHAVIOR IN LAND TREATMENT OF WASTEWATER

H.M. Selim and I.K. Iskandar

INTRODUCTION

In land treatment, nitrogen is almost always the factor limiting the rate of wastewater application. Excessive nitrate nitrogen concentration in groundwater is of great health concern due to its association with infant methemoglobinemia (blue baby syndrome) and eutrophication of natural waters. Consideration of land treatment as an alternative to advanced waste treatment has been hampered by the lack of scientific data on the fate of N that would allow efficient and cost-effective design of systems without incurring health risks.

The N behavior in land treatment is affected by numerous physical, chemical and biological processes and environmental conditions. Iskandar and Selim (1978) evaluated existing models for prediction of NO_3-N in percolate water in land treatment. They concluded that several models developed to describe one or more processes in agricultural regimes can be adapted for land treatment. However, existing large models being used for prediction of N transformation and transport in agricultural land must be modified and simplified for use under land treatment conditions. The fact that nitrogen is applied in small amounts repeatedly (most often weekly) in land treatment, in contrast to normal agricultural fertilizing practice, should produce significant differences in the nitrogen transformation processes. Also, the soils under land treatment are most often near or above field capacity so that the water flow pattern as well as N transformation processes will vary significantly from those of an agricultural regime.

The objectives of this report are to describe a simplified model for prediction of nitrogen behavior in slow and rapid infiltration land treatment systems. Model development, computer program listing and documentation and sensitivity analysis of model parameters are included. Validation of the developed model will be the subject of a later report.

THE MODEL

Modeling objectives

The objectives of developing a dynamic nitrogen model were to

1. Develop a computer model for N behavior to simulate the physical, chemical and biological processes in slow and rapid infiltration systems.
2. Enable prediction of NO_3-N concentration in soil solution and leachate with time and space.
3. Assist in estimating the application rate and schedule of water and nitrogen to a land treatment system.
4. Improve land treatment management techniques for better renovation of wastewater and less detrimental impact on the environment.
5. Point out the area(s) of research need, based on model sensitivity analysis and availability of information in the literature.

Main features

The main feature of the computer program is that it is valid for uniform as well as multilayered or stratified soil profiles. In addition, the program is flexible and is designed to incorporate the following (input) conditions as desired:

1. Rate of wastewater application.
2. Duration of wastewater application.
3. Depth of individual soil layers.

4. Concentration of ammonium and nitrate in the wastewater.

5. Wastewater application cycle, i.e. scheduling.

6. Soil water properties and nitrogen transformation mechanisms for individual soil layers.

7. Plant root distribution and growth in the soil.

8. Rate of nitrogen uptake by plants.

9. Evapotranspiration rate.

10. Initial distribution of water and nitrogen species in the soil profile.

General description

Figure 1 shows a block diagram of the simplified model presented in this report. The model is formed of two main submodels. The first is a water flow submodel which describes wastewater infiltration, water movement in the soil profile, and rate of plant uptake of water with soil depth and time. The second is a nitrogen submodel which describes the transport and transformations of N species in the soil as well as nitrogen uptake by plants. The model also includes several subroutines which account for initial and boundary conditions, plant root distribution in the soil, soil water properties, and nitrogen transformation processes (ion exchange, nitrification and denitrification). A detailed flow chart of the model and description of all subroutines are presented in a later section.

Water flow equations and boundary conditions

In order to describe the nitrogen transformation and transport in saturated-unsaturated soil profiles under transient flow conditions, the following water flow equation (Childs 1969) must be solved:

$$\partial\theta/\partial t = (\partial/\partial z)\,[K(h)\,\partial h/\partial z] - \partial K(h)/\partial z - A(z,\theta) \tag{1}$$

where

θ = soil water content (cm^3/cm^3)
h = soil water pressure head (cm)
$K(h)$ = soil hydraulic conductivity (cm/h)
$A(z,\theta)$ = rate of water extraction (cm^3/h cm^3)
t = time (h)
z = depth in the soil (cm).

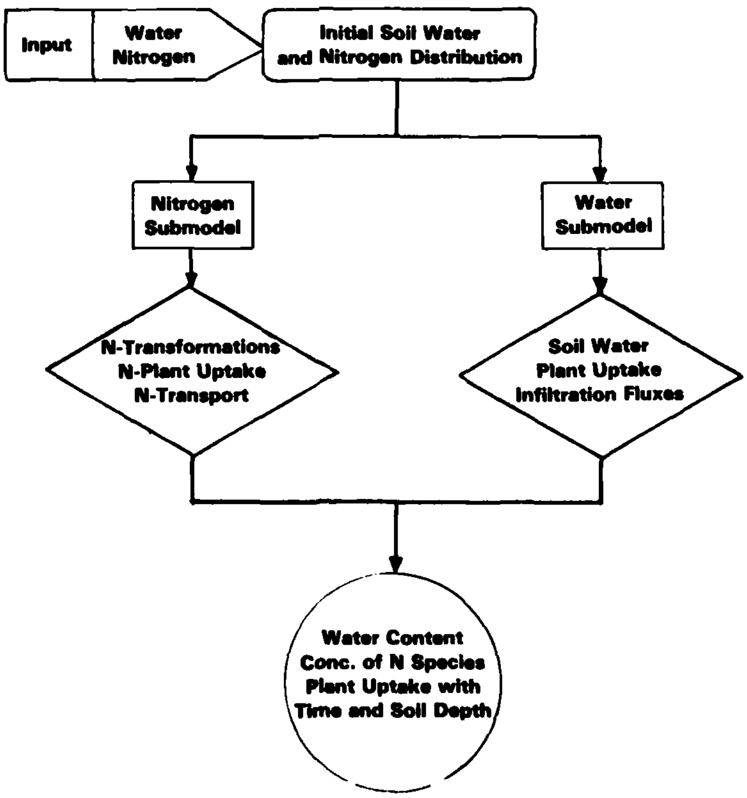

Figure 1. Diagram of the simplified nitrogen model showing the water and the nitrogen submodels.

Equation 1 is commonly known as the *h*-form of the water flow equation. This equation was chosen over the diffusivity form (Selim 1978), since it allows not only for saturated-unsaturated flow but it also allows soil stratification or layering of the soil profile. In solving eq 1, the left-hand term must be transformed such that

$$\partial\theta/\partial t = (\partial\theta/\partial h)\,(\partial h/\partial t) = \mathrm{Cap}\,(h)\,\partial h/\partial t \qquad (2)$$

where Cap (h) is the soil water capacity term (cm^{-1}) which is determined using the appropriate soil water characteristic relationship (θ vs h).

In solving eq 1 for multilayered soil profiles, the soil water hydraulic conductivity $K(h)$ and the soil water capacity Cap(h) must be provided for each soil layer. In addition, the soil water initial and boundary conditions must be specified. The initial condition is dictated by the initial distribution of θ or h in the soil profile at some assumed (starting) time. The boundary conditions at the soil surface and at some depth L below the soil surface must be provided.

Soil surface boundary conditions

Two soil surface boundary conditions are normally encountered under field conditions: 1) the water head boundary condition and 2) the water flux boundary condition.

Water head boundary condition

This condition is used when water ponding, of some height h above the soil surface, is encountered. The height h may be considered as a variable with time, i.e. $h(t)$, in order to allow for fluctuations during wastewater application and rainfall:

$$h = h_0(t), \qquad \text{at} \qquad z = 0 \qquad (3)$$

This boundary condition is also used when the soil surface is under suction, i.e. the water content at the surface is below saturation. In such case, $h(t)$ is negative and is a measure of the soil water suction (negative pressure) at the soil surface.

Water flux boundary condition

This condition is imposed when a constant or time-dependent flux (or intensity) $q(t)$ of wastewater (or rainfall) is applied at the soil surface. It also allows for evaporation between rainfall or irrigation events. This condition can be written as

$$q(t) = -\ K(h)\,\partial h/\partial z + K(h), \quad \text{at} \ z = 0 \qquad (4)$$

Bottom boundary conditions

At some depth L below the soil surface, three boundary conditions may be encountered: 1) an impervious barrier, 2) a soil profile extending to great depth, and 3) a groundwater table.

Impervious barrier

This boundary condition is used when an impermeable layer (e.g. a heavy clay layer) is encountered at some soil depth. Water flow across such a barrier is negligible. The boundary condition for an impervious barrier may be expressed as

$$-K(h)\,\partial h/\partial z + K(h) = 0, \quad \text{at} \quad z = L. \qquad (5)$$

Soil profile extends to a great depth

In this case, the soil profile is regarded as a semi-infinite medium. Thus, it is assumed that at great depth the change in soil water suction is zero:

$$\partial h/\partial z = 0, \qquad z \to \infty. \qquad (6)$$

Such a boundary condition may be used if the soil profile is well-drained and of significant depth.

Groundwater table

If a water table is encountered at some depth L in the soil profile, the water content θ is maintained at saturation θ_s at all times. Therefore,

$$\theta = \theta_s \quad z = L, \quad t > 0. \qquad (7)$$

Furthermore, the soil water suction or pressure head is

$$h = 0 \quad z = L, \quad t \geq 0 \qquad (8)$$

In addition to the above-mentioned boundary conditions, other conditions are needed in order to describe the water flow at the interface between soil layers in multilayered or stratified soil profiles. For example, we may consider a soil profile consisting of three soil layers: I, II, and III. The length of each soil layer is indicated by L_1, L_2, and L_3 (see Fig. 2). The appropriate boundary conditions at the interface between two soil layers are (Selim 1978).

$$h_{\mathrm{I}} = h_{\mathrm{II}}, \quad z = L_1, \quad t > 0, \qquad (9)$$

$$h_{\mathrm{II}} = h_{\mathrm{III}}, \quad z = L_1 + L_2, \quad t > 0, \qquad (10)$$

where h_{I}, h_{II} and h_{III} are the pressure heads in layers I, II, and III, respectively. These boundary conditions

SOIL SURFACE

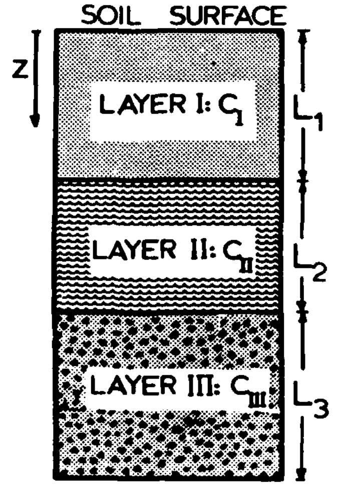

Figure 2. Schematic diagram of a multilayered soil profile.

are necessary in order to maintain the continuity of the pressure head h at the boundary interfaces.

Nitrogen transformations and transport equations and boundary conditions

In the development of this simplified model, three major approximations have been made. The first simplification is that the nitrification process was considered as a single step, i.e. $NH_4^+ \rightarrow NO_3^-$ rather than a two-step process ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$). Such an assumption is considered adequate, since NO_2 in most soils under neutral pH conditions is rapidly oxidized to NO_3. The second major simplification is that the organic-N phase was not incorporated in the model. It was assumed that the net change (over a short period of time) in organic-N content is small and the rate of nitrogen mineralization as well as immobilization are extremely slow. The third simplification is that oxygen diffusion in the soil profile was not incorporated. Therefore, denitrification of nitrate in the soil was assumed to be a function of the degree of soil water saturation only.

The nitrogen transformation processes considered were: nitrification of NH_4^+ to NO_3^-, denitrification of NO_3^-, and ion exchange of ~~NH_4^+ (see~~ Fig. 3). The ion-exchange process was assumed to be instantaneous, whereas nitrification and denitrification processes were of the first-order kinetic type (Selim et al. 1976 and Selim and Iskandar 1978). A distribution coefficient K_D (cm^3/g) was used to describe the instantaneous (reversible) ammonium release from exchange sites to soil solution. The first-order kinetic rate coefficients associated with the nitrification and denitrification processes were k_1 and k_2 (h^{-1}), respectively. The assumptions that these nitrogen transformation processes follow first-order kinetic reaction were based on studies by McLaren (1970, 1971), Mehran and Tanji (1974), and Hagin and Amberger (1974).

Soil environmental conditions such as soil suction, aeration, temperature, organic matter content, and pH have significant effects on the various nitrogen transformation mechanisms. In order to incorporate these factors, the rate coefficients were expressed (Selim et al. 1976) as

$$k_1 = \bar{k}_1 f_1, \tag{11}$$

$$k_2 = \bar{k}_2 f_2, \tag{12}$$

where $\bar{k}_1$ and $\bar{k}_2$ are considered constants for each individual soil layer and f_1 and f_2 are empirical functions which describe the influence of the previously mentioned environmental conditions on nitrification and denitrification, respectively.

The transport of NH_4-N and NO_3-N in the soil solution occurs as a result of molecular diffusion, mechanical dispersion, and convection or mass flow. Molecular diffusion results from the random thermal movement of molecules, whereas mechanical dispersion results from the velocity distribution of water in the soil pore space. For all soil layers, a single dispersion coefficient D is commonly used which combines mechanical dispersion and diffusion. Therefore, the convective-dispersive equations governing NH_4-N and NO_3-N transport may be expressed (Misra et al. 1974, Davidson et al. 1977, and Selim and Iskandar 1978) as

$$\partial(\theta C)/\partial t = (\partial/\partial z)\,(\theta D\,\partial C/\partial z) - \partial(vC)/\partial z$$
$$-\theta\, k_1 C - \rho\,\partial S/\partial t - q_{NH4} \tag{13}$$

$$\partial(\theta Y)/\partial t = (\partial/\partial z)\,(\theta D\,\partial Y/\partial z) - \partial(vY)/\partial z$$
$$+\theta k_1 C - \theta k_2 Y - q_{NO3} \tag{14}$$

where C = concentration of NH_4-N in soil solution ($\mu g/cm^3$)
Y = concentration of NO_3-N in soil solution ($\mu g/cm^3$)

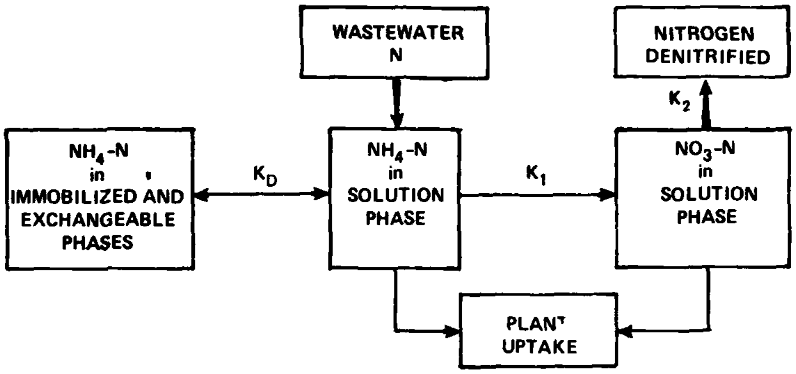

Figure 3. Schematic diagram of the nitrogen transformation processes considered in the nitrogen submodel.

D = solute dispersion coefficient (cm^2/h)
v = soil water flux (cm/h)
S = amount of NH_4 in the exchangeable phase per gram of soil ($\mu g/g$)
ρ = soil bulk density (g/cm^3)
k_1 and k_2 = kinetic rate coefficients for nitrification and denitrification ($^{-1}$), respectively
q_{NH4} and q_{NO3} = rates of plant uptake of NH_4-N and NO_3-N per unit soil volume ($\mu g/cm^3$ h), respectively.

The first two terms on the right-hand side of eq 13 and 14 account for solute transport, and are usually called the dispersion and mass flow terms, respectively. The third and fourth terms of eq 13 account for nitrification and ion exchange, respectively, of NH_4-N. Similarly, the third and fourth terms of eq 14 represent the nitrification and denitrification processes, respectively. The ion exchange process governing NH_4-N adsorption-desorption was assumed to be of the linear Freundlich type, i.e.

$$S = K_D C, \text{ or } \partial S/\partial t = K_D\ \partial C/\partial t, \tag{15}$$

where K_D, commonly called the distribution coefficient (cm^3/g), represents the ratio between the amount of NH_4-N adsorbed and its concentration in the soil solution.

Rearrangements of eq 13 and incorporation of eq 15 yield the following simplified equation for ammonium transport and transformation:

$$R\ \partial C/\partial t = D\ \partial^2 C/\partial z^2 - (V/\theta)\ \partial C/\partial z - k_1\ C - (q_{NH4}/\theta) \tag{16}$$

where R is the retardation factor for ammonium exchange:

$$R = 1 + \rho K_D/\theta. \tag{17a}$$

and V is expressed as

$$V = v - D\ \partial\theta/\partial z. \tag{17b}$$

Similarly, eq 14 after rearrangements yields the following equation for nitrate transport and transformations:

$$\partial Y/\partial t = D\ \partial^2 Y/\partial z^2 - (V/\theta)\ \partial Y/\partial z + k_1 C - k_2 Y - (q_{NO3}/\theta). \tag{18}$$

It should be noted that in the case of multilayered soil profiles, soil water and nitrogen transformation parameters (e.g. ρ, $K(h)$, k_D, k_1, k_2, etc.) must be provided for each individual soil layer.

To solve the ammonium and nitrate transport and transformation equations, eq 16 and 18, the initial and boundary conditions must be specified. During wastewater application, the soil surface boundary conditions for eq 16 and 18, respectively, are:

$$vC_s = -\theta D\ \partial C/\partial z + vC, \quad z = 0, \quad t < T, \tag{19}$$

and

$$vY_s = -\theta D \, \partial Y/\partial z + vY, \quad z = 0, \quad t < T, \tag{20}$$

where

C_s and Y_s = NH_4-N and NO_3-N concentrations in applied wastewater, respectively (μg N/ml)

$v = q(t)$, flux or intensity of wastewater application (cm/h)

T = duration of wastewater application (h).

The above equations, eq 19 and 20, are commonly called the dispersive-convective boundary conditions which can also be applied to describe rainfall events. In such a case, the intensity and duration of rainfall (v and T) must be specified and C_s and Y_s in rainwater may be considered zero.

Following the termination of a wastewater application or rainfall event ($t > T$), the surface boundary conditions become

$$\partial C/\partial z = 0, \quad z = 0, t > T \tag{21}$$

and

$$\partial Y/\partial z = 0, \quad z = 0, t > T \tag{22}$$

Furthermore, the boundary condition at the bottom of the soil profile ($z = L$) is

$$\partial C/\partial z = 0, \quad z = L, t \geq 0 \tag{23}$$

$$\partial Y/\partial z = 0, \quad z = L, t \geq 0 \tag{24}$$

In addition, the boundary conditions at the boundary interface between two soil layers (see Fig. 2) may be written as

$$C_{I} = C_{II} \text{ and } Y_{I} = Y_{II}, \quad z = L_1, t \geq 0 \tag{25}$$

$$C_{II} = C_{III} \text{ and } Y_{II} = Y_{III}, \quad z = L_1 + L_2, t \geq 0 \tag{26}$$

where the subscripts I, II, and III refer to the first, second, and third soil layers, respectively. Similar to the equations for water flow, eq 25 and 25 above are needed in order to maintain the continuity of NH_4-N and NO_3-N concentrations at the boundary interface.

Water and nitrogen uptake by plants

Plant uptake of water and nitrogen from the soil root zone is an important factor in the renovation of wastewater applied to soil. Recent studies have shown that in a slow infiltration land treatment system, a major portion of applied wastewater nitrogen (up to 70%) was taken up by plants (Iskandar et al. 1976). Therefore in modeling the fate of nitrogen in soil, it is important to incorporate a plant uptake model that provides accurate predictions of the rate of plant uptake during the growing season. However, as Nye and Tinker (1977) pointed out, the major difficulties in modeling of plant uptake are the lack of quantitative measurements on the root development and distribution as well as the inaccuracy of soil physical measurements.

At present there are two approaches for modeling plant root uptake of water and nutrients in soils: 1) a "microscopic" approach where the water and nutrient flux to a single root is considered (Nye and Marriot 1969, Claassen and Barber 1976), and 2) a "macroscopic" approach where the root system as a whole is considered (Molz and Remson 1970, Davidson et al. 1977, Selim and Iskandar 1978). In this simplified model the macroscopic approach is used to describe the water as well as the nitrogen uptake by plant roots. The extraction or sink term $A(z, \theta)$ for water uptake (eq 1) is represented as

$$A(z, \theta) = T R(z) K(h) / \int_0^Z R(z) K(h) \, dz \tag{27}$$

where Z is the maximum depth of the root zone in the soil (cm) and T the evapotranspiration rate per unit area of soil surface (cm/h). The term $R(z)$ is the root distribution as a function of depth in the soil profile. Specifically the root distribution $R(z)$ is the length of roots (cm) as a function of soil depth and time. Equation 27 was proposed by Molz and Remson (1970) and was successfully used in predicting the water uptake when the evapotranspiration rate T was met. Such conditions are satisfied when high soil water contents (low suctions) are maintained in the soil root zone, such as in land treatment-slow infiltration systems.

The terms q_{NH4} and q_{NO3} in eq 16 and 18 account for the rate of uptake of NH_4-N and NO_3-N, respectively. Here the Michaelis-Menten approach was used to determine the rate of N uptake as a function of root density and concentration of ammonium and nitrate in the soil solution. Therefore the rate of N uptake may be expressed as:

$$q_{NH4} = I_{max}\, C/[K_m+(C+Y)] \quad (28)$$

$$q_{NO3} = I_{max}\, Y/[K_m+(C+Y)] \quad (29)$$

In eq 28 and 29, I_{max} is the maximum rate of N uptake per unit root length (μg/h cm) when the concentration of nitrogen in the soil solution is extremely high, and the term K_m is the Michaelis constant (μg/ml) which is the concentration of N at ½ I_{max}. Both I_{max} and K_m are determined by measuring N uptake in solution cultures having different nitrogen concentrations (Claassen and Barber 1976). In this model the values of I_{max} and K_m were considered similar for both ammonium and nitrate uptake*.

Method of model solution

The water and nitrogen equations (eq 1, 16 and 18) are nonlinear partial differential equations and cannot be solved analytically. Therefore, these equations, subject to the above described initial and boundary conditions, were solved using numerical analysis techniques. The method of solution was by explicit-implicit finite difference approximation (Henrici 1962, Varga 1962, and Carnahan et al. 1969). This method was successfully used by Selim (1978) for transient water and solute movement in multilayered soil profiles. Finite difference approximations provide distributions of soil water content, water suction, NH_4-N and NO_3-N concentrations at incremental distances Δz in the soil profile, and discrete time steps Δt. In finite difference form, a variable such as h is expressed as $h_i^n = h(z, t) = h(i\Delta z, n\Delta t)$ where $i = 1, 2, 3, ..., I$, and $n = 1, 2, ...$ Therefore, the finite difference approximation for the water flow equation (eq 1) is

$$\begin{aligned}\mathrm{Cap}\,(h_i^{n+1/2})\,[h_i^{n+1}-h_i^n] &= \gamma\, K(h_{i+1/2}^{n+1/2})\,[h_{i+1}^{n+1}-h_i^{n+1}]\\ &-\gamma\, K(h_{i-1/2}^{n+1/2})\,[h_i^{n+1}-h_{i-1}^{n+1}]\\ &+\gamma\, K(h_{i+1/2}^{n+1/2})\,[h_{i+1}^{n}-h_i^{n}]\\ &-\gamma\, K(h_{i-1/2}^{n+1/2})\,[h_i^{n}-h_{i-1}^{n}]\\ &-\beta[K(h_{i+1/2}^n)+K(h_{i-1/2}^n)]-\Delta t\, A_i^n \end{aligned} \quad (30)$$

where $\gamma = \Delta t/2(\Delta z)^2$ and $\beta = \Delta t/\Delta z$. Similarly, finite difference approximations for the equation governing NH_4-N transport and transformation (eq 16) may be expressed as

$$\begin{aligned}R_i^{n+1}\,[C_i^{n+1}-C_i^n] &= \gamma D\,[C_{i+1}^{n+1}-2C_i^{n+1}+C_{i-1}^{n+1}]\\ &+\gamma D\,[C_{i+1}^{n}-2C_i^{n}+C_{i-1}^{n}]\\ &-(V/\theta)_i^{n+1}\,\beta[C_{i+1}^{n+1}-C_i^{n+1}]\\ &-\Delta t\, k_7\, C_i^n-\Delta t\,(q_{NH4}/\theta)_i^n \end{aligned} \quad (31)$$

and the finite difference approximation for NO_3-N (eq 18) is

$$\begin{aligned}Y_i^{n+1}-Y_i^n &= \gamma D\,[Y_{i+1}^{n+1}-2Y_i^{n+1}+Y_{i-1}^{n+1}]\\ &+\gamma D\,[Y_{i+1}^{n}-2Y_i^{n}+Y_{i-1}^{n}]\\ &-(V/\theta)_i^{n+1}\,\beta\,[Y_{i+1}^{n+1}-Y_i^{n+1}]\\ &+\Delta t\, k_1\, C_i^n-\Delta t\, k_2\, Y_i^n-\Delta T\,(q_{NO3}/\theta)_i^n. \end{aligned} \quad (32)$$

Equations 30, 31, and 32 are nonlinear since Cap (h_i^{n+1}) and $K(h_i^{n+1/2})$ are dependent on $h_i^{n+1/2}$ for which solutions are being sought. The iteration method described by Remson et al. (1971) is usually used to predict $h^{n+1/2}$ using h^n. Selim and Kirkham (1973) showed that solution of the water flow equation can be approximated satisfactorily using h^n when smaller values of Δt than required for stable solution are used. This simplifies the computation considerably since the system of equations becomes linear. Accordingly, the approximations, $K(h_i^{n+1/2}) = K(h_i^n)$ and Cap $(h_i^{n+1/2})$ = Cap (h_i^n), were made.

Incorporation of initial and boundary conditions in their finite difference forms and rearrangement of eq 30, 31, and 32 yield three linear systems of equations. Rearranging the finite difference form of water flow equation (eq 30) yields

$$d_i^n\, h_{i-1}^{n+1}+e_i^n\, h_i^{n+1}+g_i^n\, h_{i+1}^{n+1} = w_i^n \quad (33)$$

where
$$\begin{aligned} d_i^n &= -\gamma\, K(h_{i-1/2}^n)\\ e_i^n &= \mathrm{Cap}\,(h_i^n)+\gamma\,[K(h_{i+1/2}^n)+K(h_{i-1/2}^n)]\\ g_i^n &= -\gamma\, K(h_{i+1/2}^n)\\ w_i^n &= \mathrm{Cap}\,(h_i^n)\, h_i^n+\gamma\, K(h_{i-1/2}^n)\, h_{i-1}^n\\ &\quad -\gamma\,[K(h_{i+1/2}^n)+K(h_{i-1/2}^n)]\, h_i^n\\ &\quad +\gamma\, K(h_{i+1/2}^n)\, h_{i+1}^n \end{aligned}$$

*S.A. Barber, Department of Agronomy, Purdue University, personal communication 1979.

$$-\beta\,[K(h^n_{i+1/2})+K(h^n_{i-1/2})]-\Delta t\,A^n_i.$$

By including the initial and boundary conditions in their finite difference forms, eq 33 can be written in matrix-vector notation as

$$B\vec{h}^{\,n+1}=\vec{w} \tag{34}$$

where B is a tridiagonal real matrix and $\vec{h}$ and $\vec{w}$ denote the associated real column vectors (the arrows indicate vectors). The matrix B may be written as

$$B\equiv\begin{bmatrix} e^n_1\; g^n_1 & & & & & \\ d^n_2\; e^n_2\; g^n_2 & & & & & \\ & d^n_3\; e^n_3\; g^n_3 & & & & \\ & & \cdots & & & \\ & & & \cdots & & \\ & & & & d^n_{I-1}\; e^n_{I-1}\; g^n_{I-1} & \\ & & & & & d^n_I\; e^n_I \end{bmatrix} \tag{35}$$

The coefficients of the main diagonal of the matrix B, in absolute values, are greater than the raw sum of the off-diagonal coefficients. Hence, the matrix B is strictly diagonally dominant (Varga 1962, p. 23). Therefore the matrix is nonsingular, and there exists a solution $\vec{h}^{\,n+1}$ for the matrix vector equation (eq 34) that is unique. The tridiagonal system of equations was solved by an adaptation of the Gaussian algorithm as described by Henrici (1962, p. 352). The second and third systems of eq 31 and 32 for NH_4-N and NO_3-N transport and transformation, respectively, were solved similarly.

It is obvious from eq 16 and 18 that nitrogen transport is dependent on θ and v, both of which are variable under transient flow conditions. Thus, in order to describe nitrogen transport for transient conditions, the water flow equation (eq 1) must be solved prior to the nitrogen transformation and transport equations. Therefore, for any time step, $n+1$, where all variables are assumed to be known at time step n, eq 30, 31, and 32 are solved sequentially until a desired time t is reached.

MODEL SENSITIVITY

In order to provide a complete sensitivity analysis of model parameters, it is essential to investigate each parameter separately. This is usually achieved by first studying the influence of each parameter on model results for a wide range of values, with all other parameters remaining unchanged. Second, when two or more parameters prove to be more significant compared to other model parameters, such two or more parameters are investigated simultaneously for a range of values. For the model presented here a complete sensitivity analysis was not attempted since a large number of model parameters were involved. Therefore, it was decided to study only selected parameters which were chosen for sensitivity analysis. These parameters are 1) the rate of nitrification (k_1), 2) the distribution coefficient (K_D) for NH_4-N ion-exchange, and 3) rate of plant uptake (I_{max}). The influence of different nitrogen transformation parameters for individual soil layers and the rate of denitrification were not investigated. Moreover, soil water properties, schedule of wastewater application and NH_4-N and NO_3-N concentrations in the wastewater remained unchanged for all cases studied.

The simultaneous transport, transformation, and plant uptake of nitrogen and water were simulated using the model presented here. Input soil and water parameters, initial and boundary conditions, etc., were similar to those of the CRREL research experimental facilities. Wastewater was assumed to contain 25 µg/ml of NH_4-N and zero nitrate content. The schedule of application was 0.5 or 1 week and the total amount of wastewater applied was 5 cm per each application. The soil parameters chosen were for a Windsor sandy loam soil having three distinct soil layers. Chemical characteristics of this soil are presented elsewhere (Iskandar et al. 1979, Iskandar and Nakano 1978). The total length of the soil profile was assumed to be 150 cm and the thicknesses of the first, second and third layers were 15, 30 and 105 cm, respectively. A water table (zero water pressure head) was assumed at the bottom (150 cm depth) of the soil profile. The soil water properties for each soil layer were described by the following mathematical expressions:

$$\theta(h)=\theta_s/[1+(-h/a)^b] \tag{36}$$

$$K(\theta)=\eta\,\exp\,(\alpha\theta). \tag{37}$$

The parameters for each soil layer were obtained by "best fit" of experimental data (Iskandar and Nakano 1978). The values of a and b were 100 and 1 for the first layer, 40 and 1 for the second layer, and 30 and 1 for the third layer, respectively. The values for parameters η and α were 9.6×10^{-4} and 27.63 for the first layer, 2.2×10^{-4} and 30.7 for the second layer, and 2.1×10^{-4} and 38.87 for the third layer, respectively. The values for water content at saturation θ_s were 0.44, 0.42 and 0.34 (cm^3/cm^3) for the first, second and third layers, respectively. Furthermore, the values for

soil bulk density ρ were 1.41 for the first layer, 1.59 for the second layer, and 1.55 g/cm^3 for the third layer.

Several nitrogen transformation rate coefficients and uptake rates were chosen in order to illustrate the significance of these processes on the fate of wastewater nitrogen in land treatment systems. The rate of nitrification $\bar{k}_1$ ranged from 0.025 to 0.5 h^{-1} whereas $\bar{k}_2$ was maintained constant at 0.01 h^{-1}. For the nitrification kinetic reaction, the function f_1 (eq 1) which describes the dependence of the reaction on soil environmental conditions remained unchanged and was expressed as a function of pressure head (Hagin and Amberger 1974):

$$f_1 = \begin{cases} 0 & h > -10 \text{ cm} \\ 0.005\,(-h-10) & h > -50 \text{ cm} \\ 0.2+0.006\,(-h-40) & h > -100 \text{ cm} \\ 0.5+0.0015\,(-h-100) & h > -433 \text{ cm} \\ 1.0-0.002\,(-h-433) & h < -433 \text{ cm.} \end{cases}$$

The denitrification function f_2 (eq 12) was considered as a function of the degree of water saturation in the soil:

$$\begin{aligned} f_2 &= 0 && \text{for } (\theta/\theta_s) < 0.8 \\ f_2 &= (\theta-0.8\,\theta_s)/0.1\,\theta_s && \text{for } 0.8 < \theta/\theta_s < 0.9 \\ f_2 &= 1 && \text{for } \theta/\theta_s > 0.9 \end{aligned}$$

where θ_s is soil water content at saturation (cm^3/cm^3). Furthermore, the value of the coefficient K_D for the ammonium exchange ranged from 0.05 to 1.5 cm^3/g. All these parameters, for the cases shown here, were similar for all three soil layers.

The root distribution $R(z)$ used in the sensitivity analysis was in the form of an exponential expression:

$$R(z) = 226 \exp(-0.1\,z)$$

This exponential function provides a sharp decrease of the root distribution (or density) with soil depth z. In this case, 77.8% of the roots were actually observed to be in the top 15 cm, 17.2% in the 15- to 30-cm soil depth and only 5% of the roots in the 30- to 60-cm soil depth. This mathematical expression for root distribution was obtained from field measurements of root length with depth (Iskandar unpublished data 1979). It represents a two-year-old mixture of reed canarygrass and tall fescue grass irrigated with 5 cm of wastewater weekly. Furthermore, a value of 1.0 ppm for the Michaelis constant K_m was chosen for all cases presented here. Values of I_{max} ranged from 0.0005 to 0.0015 μg N/h cm of roots.

In order to illustrate the capabilities of this model, simulated water content and nitrogen distributions in the soil are presented in Figures 4, 5 and 6 for one week following the application of 5 cm of wastewater. In this case the rate coefficients for nitrification $\bar{k}_1$ were taken as 0.1 h^{-1} and K_D as 0.25 cm^3/g. Following the application of 5 cm of wastewater, which contained 25 ppm of NH_4-N, we see that NH_4-N concentration in the soil solution decreased drastically with time. This disappearance of NH_4-N was due to its conversion to NO_3-N through nitrification and to uptake by plants. The NO_3-N distributions shown in Figure 6 show that the maximum peak concentration occurred on day 1. This is primarily due to the initial NO_3-N in the soil profile. Furthermore, the initial peak, which was located at the 15-cm depth, penetrated to a depth of 35 cm during the first day. Downward movements of the nitrate peak to lower soil depths continued with time at a decreasing rate. This slow movement of nitrate in the soil profile was due to the continuing decrease of soil water flow during water redistribution, i.e. following the infiltration of applied wastewater. Meanwhile, the nitrate concentration of the leachate (z = 150 cm) continued to increase with time.

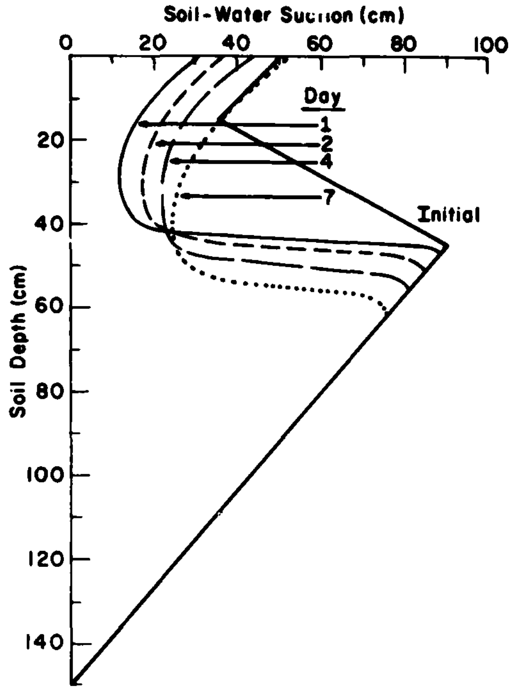

Figure 4. Simulated soil water suction distributions in a Windsor soil for one week following application of 5 cm of wastewater

Figure 7 shows the cumulative nitrogen uptake by plants with time during weekly application of wastewater. Simulated results show that NH_4-N uptake was much greater than that for NO_3-N at all times. This

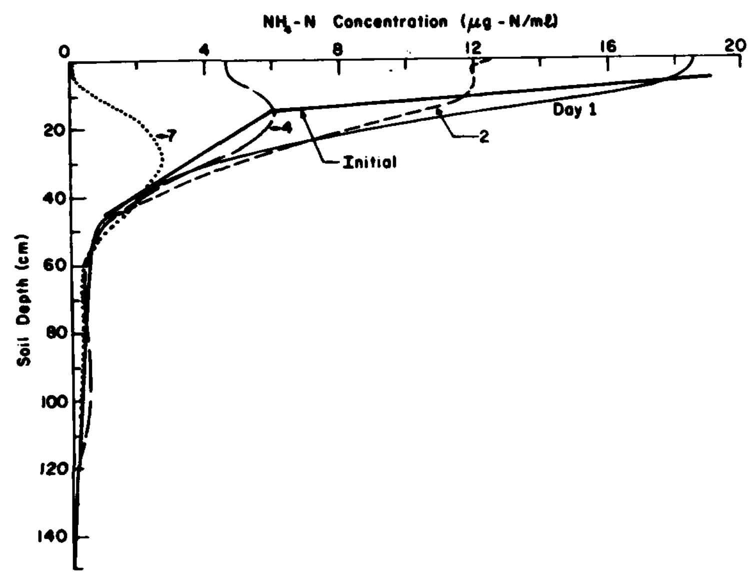

Figure 5. Simulated NH_4-N distributions for one week following wastewater application and for $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 0.25\ cm^3/g$ and $I_{max} = 0.001\ \mu g\ N/h\ cm$.

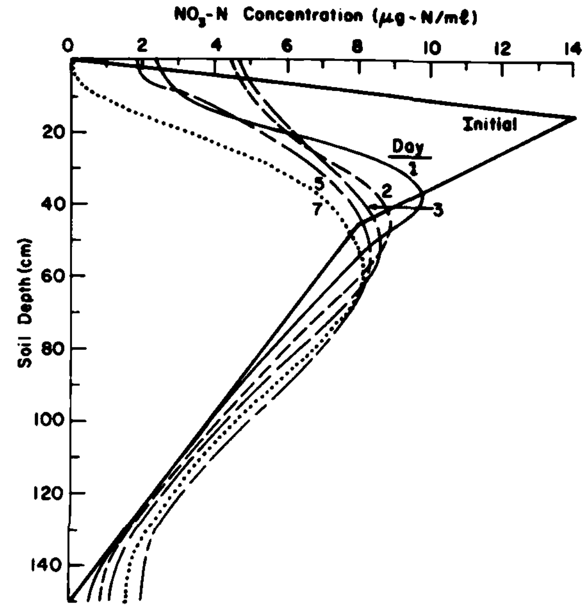

Figure 6. Simulated NO_3-N distributions for one week following waster application and for $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 0.25\ cm^3/g$ and $I_{max} = 0.001\ \mu g\ N/h\ cm$.

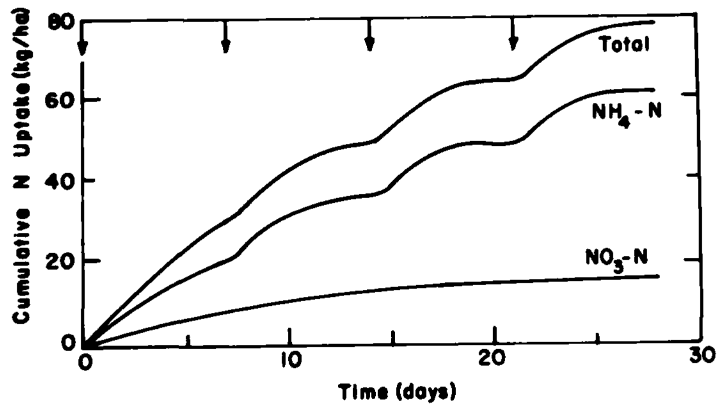

Figure 7. Cumulative NO_3-N and NH_4-N uptake with time for $I_{max} = 0.001\ \mu g\ N/h\ cm$. Arrows indicate wastewater applications events.

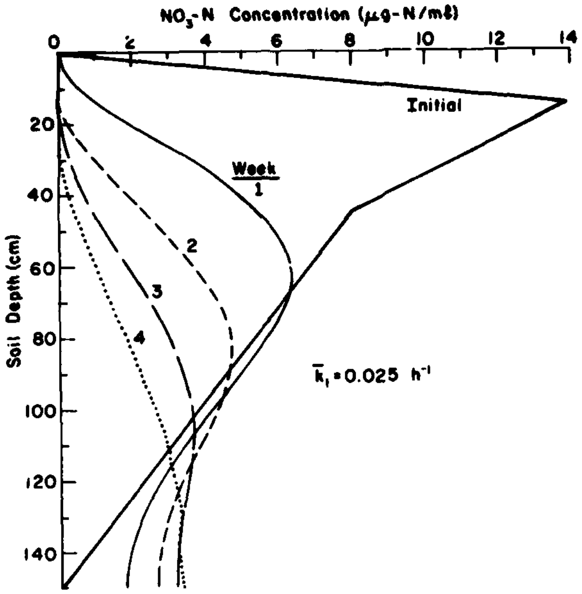

Figure 8. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1$ = 0.025 h^{-1}, K_D = 0.25 cm^3/g and I_{max} = 0.001 μg N/h cm.

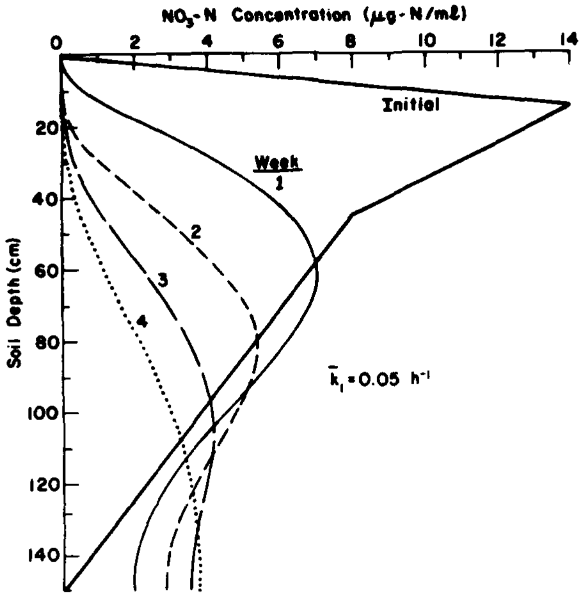

Figure 9. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1$ = 0.05 h^{-1}, K_D = 0.25 cm^3/g and I_{max} = 0.001 μg N/h cm.

is due to the low concentration of NO_3-N in the top portion of the soil profile for an extended period of time. In contrast, the NH_4-N remained at shallow soil depth due to ion-exchange which resulted in higher NH_4-N uptake. It should be noted that in the simulation, 77.8% of plant roots were in the top 15 cm of the soil profile.

Figures 8-12 show the influence of changing the nitrification rate coefficients $\bar{k}_1$ on the nitrate distribution in the soil profile during weekly application of wastewater. In the cases considered, the values of $\bar{k}_1$ range from 0.025 to 0.5 h^{-1}, whereas K_D and I_{max} remained constant (K_D = 0.25 cm^3/g and I_{max} = 0.001 μg-N/h cm). The simulated results show that as the rate of nitrification increased, the maximum peak concentration also increased at the end of the weekly wastewater applications. These increases in peak concentrations were obviously due to the imposed increase in faster conversion of NH_4-N to NO_3-N in the soil. Furthermore, maximum peak concentrations were locatec at shallower soil depths as $\bar{k}_1$ increased. The location of the peak closer to the soil surface coincides with that for NH_4-N. The simulated results also show that the rate of nitrification directly influences the effluent concentration (at z = 150 cm). As expected, the effluent NO_3-N concentration (at any particular time) increased as the rate of nitrification increased.

Figure 13 shows the effect of changing the rate of nitrification on the total amounts of NH_4-N and NO_3-N in the soil profile during weekly wastewater application. These simulated results were obtained by integrating the nitrogen concentration profiles shown in Figures 8-12. As expected, as the rate of NH_4-N conversion to NO_3-N increased, the total amount of NH_4-N in the soil profile decreased and the total amount of NO_3-N in the soil profile increased. It should also be emphasized here that the relationship between N in the soil profile and $\bar{k}_1$ (Fig. 13) is a nonlinear one. This is clearly shown by the leveling of the curves for $\bar{k}_1$ greater than 0.2 h^{-1}. Such leveling of the curves indicates that, for the cases considered, the influence of $\bar{k}_1$ on the fate of nitrogen is negligible for $\bar{k}_1$ > 0.2 h^{-1}. Therefore, it is expected that beyond such $\bar{k}_1$ values, other factors which affect the amount of NH_4-N in the soil profile (such as the rate of N uptake, the ion-exchange of NH_4-N, and the amount of weekly wastewater applied) will influence the NO_3-N in the soil profile. For example, if the amount of weekly wastewater were 50 rather than 25 ppm, it would be reasonable to expect that the leveling will be at a higher $\bar{k}_1$ value than 0.2 h^{-1}. The opposite would be true for a reduced rate of plant uptake.

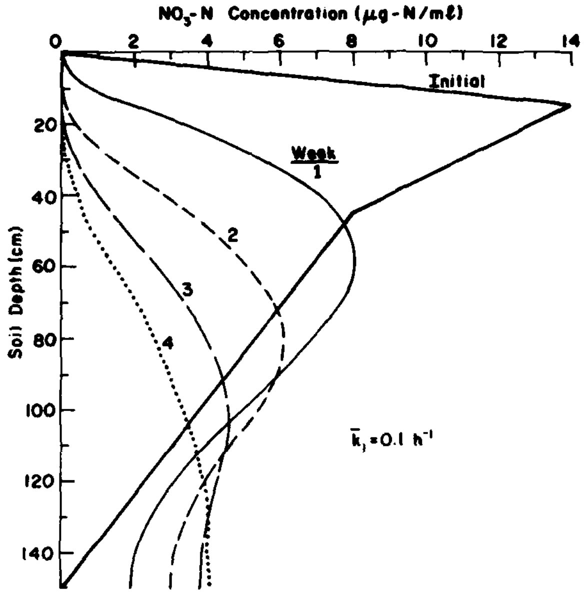

Figure 10. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 0.25\ cm^3/g$ and $I_{max} = 0.001\ \mu g\ N/h\ cm$.

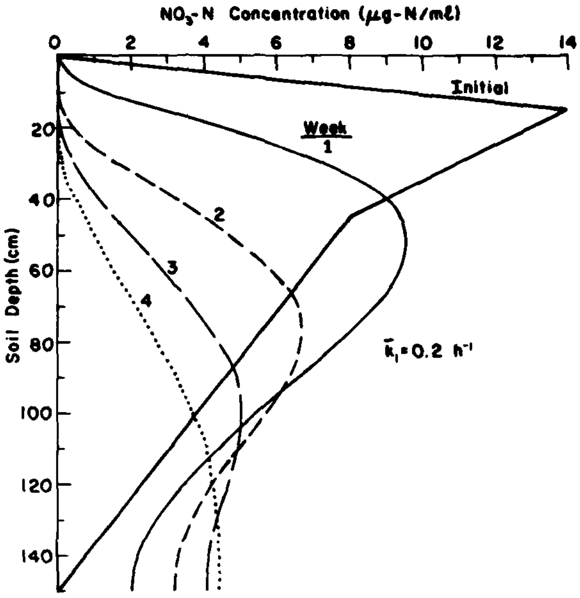

Figure 11. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.2\ h^{-1}$, $K_D = 0.25\ cm^3/g$ and $I_{max} = 0.001\ \mu g\ N/h\ cm$.

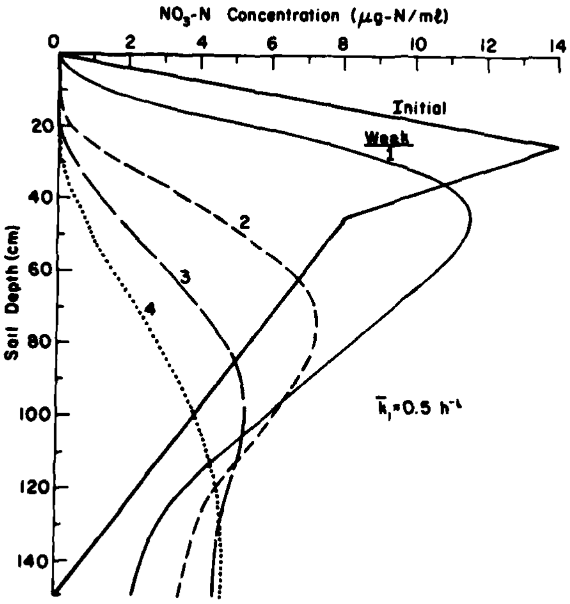

Figure 12. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.5\ h^{-1}$, $K_D = 0.05\ cm^3/g$ and $I_{max} = 0.001\ \mu g\ N/h\ cm$.

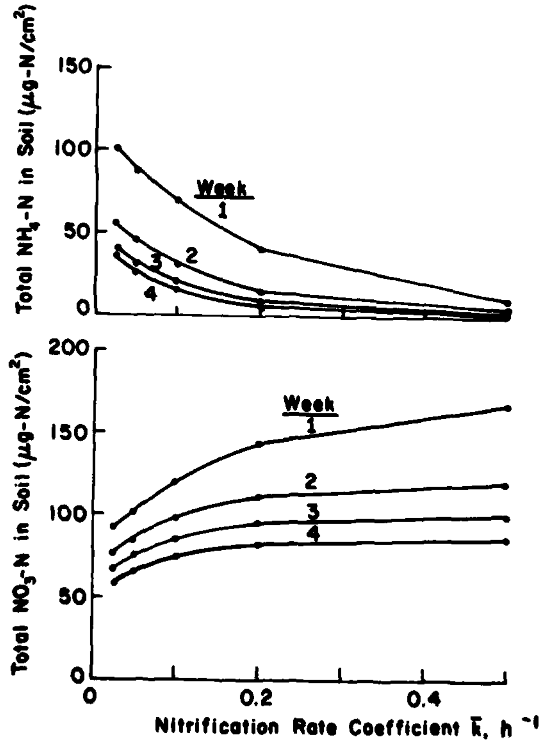

Figure 13. Nitrification rate coefficient $\bar{k}_1$ vs total NH_4-N and NO_3-N in the soil profile.

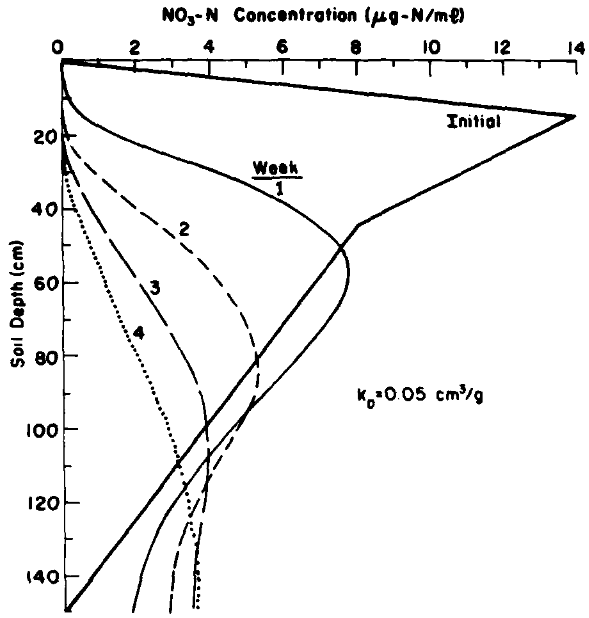

Figure 14. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 0.05\ cm^3/g$ and $I_{max} = 0.001$ µg N/h cm.

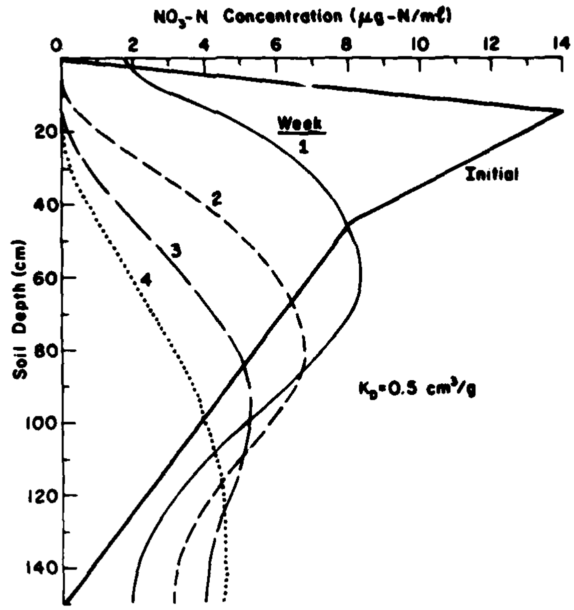

Figure 15. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 0.5\ cm^3/g$ and $I_{max} = 0.001$ µg N/h cm.

The influence of a range of K_D values on the fate of wastewater nitrogen is shown in Figures 14-16. The K_D values considered ranged from 0.05 to 1.5 cm^3/g which simulates a wide range of soils having different cation exchange capacities. The $\bar{k}_1$ and I_{max} values remained constant ($\bar{k}_1 = 0.1\ h^{-1}$ and $I_{max} = 0.001$ µg-N/cm h) for these cases. For small values of K_D (Fig. 14), the nitrate concentration profiles showed a rapid movement in the soil profile. Such rapid nitrate leaching is a direct result of low NH_4-N retardation in the soil profile. In contrast, for larger K_D values (Fig. 15 and 16), the retardation of NH_4-N to transport in the soil profile was greater, resulting in slower movement of NO_3-N in the soil profile. This slow movement of nitrate nitrogen is illustrated by the location of the peaks at shallow soil depths as well as higher peak concentrations.

The effect of I_{max}, the maximum rate of N uptake, on the fate of nitrogen in the soil profile as well as the cumulative N uptake are shown in Figures 17-19. Here the range of I_{max} was from 0.005 to 0.0015 µg-N/h cm of root length. All other parameters were constant: $\bar{k}_1 = 0.1\ h^{-1}$ and $K_D = 0.25\ cm^3/g$. As expected, for small values of I_{max} (Fig. 17), the NO_3-N distributions show significantly higher concentrations than for large I_{max} values. Differences in concentration distributions are clearly shown in the upper portion of the soil profile. For $I_{max} = 0.0015$ µg N/h cm, plant uptake resulted in considerable depletion of the NO_3-N in the root zone (0-30 cm). In contrast, considerable amounts of NO_3-N remained in the top soil profile for the case $I_{max} = 0.0005$ µg-N/h cm. The cumulative nitrogen uptake patterns for different values (Fig. 19) show that for $I_{max} = 0.005$ the uptake with time was linear. Such a linear relationship indicates a constant rate of nitrogen uptake with time. For this case, the maximum rate of nitrogen uptake was met, indicating an abundance of nitrogen in the soil root zone at all times. However, for large values of I_{max} the amount of nitrogen in the root zone was limited as indicated by the nonlinear uptake patterns for I_{max} of 0.001 and 0.0015 µg-N/h cm. Immediately following each weekly application, the simulated results also show a rapid increase in the nitrogen uptake as a result of the newly added nitrogen in the wastewater. However, three to four days after application of wastewater, when the nitrogen concentration in the root zone becomes small, the rate of uptake decreases drastically with time. This change of the rate of uptake with time is clearly illustrated in Figure 19 by the sudden increase followed by a leveling of the

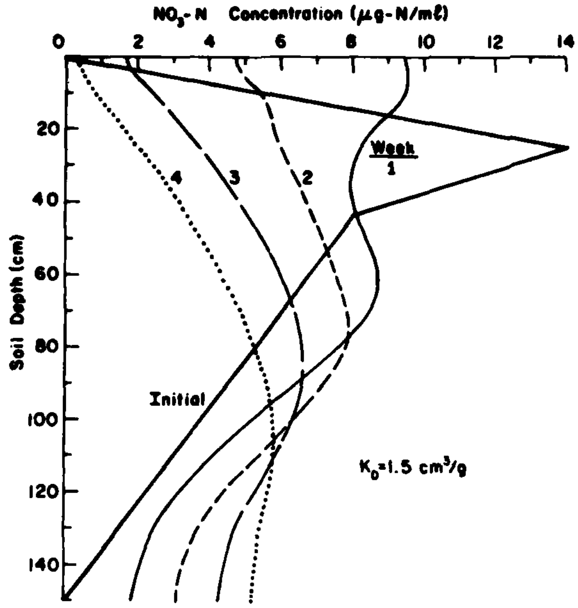

Figure 16. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 1.5\ cm^3/g$ and $I_{max} = 0.001$ µg N/h cm.

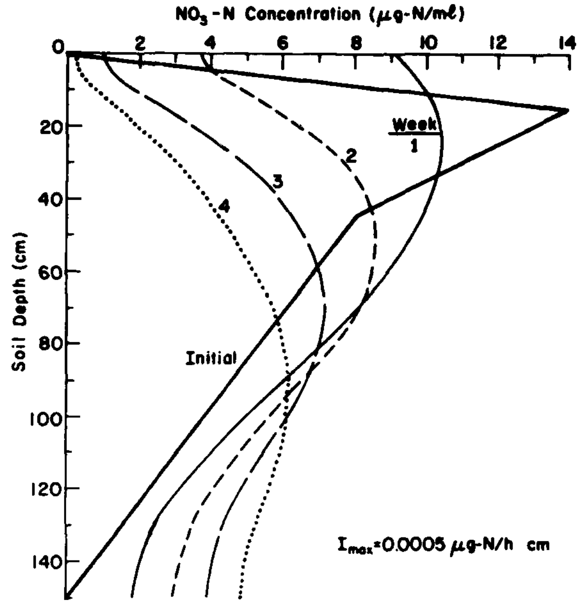

Figure 17. Simulated concentration distribution of NO_3-N in the soil profile where $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 0.25\ cm^3/g$ and $I_{max} = 0.0005$ µg N/h cm.

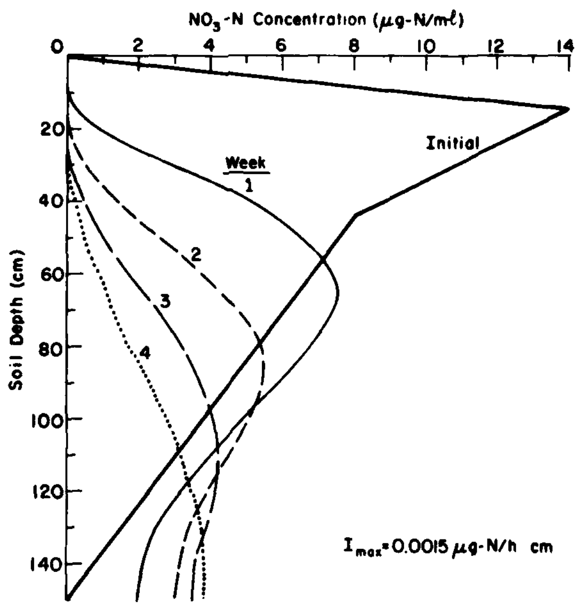

Figure 18. Simulated concentration distribution of NO_3-N in the soil profile where $\bar{k}_1 = 0.1\ h^{-1}$, $K_D = 0.25\ cm^3/g$ and $I_{max} = 0.0015$ µg N/h cm.

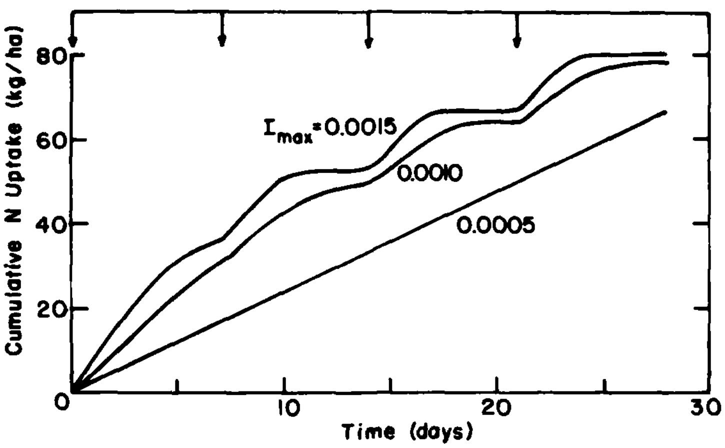

Figure 19. Cumulative N uptake with time for I_{max} of 0.0005, 0.0010 and 0.0015 μg N/h cm.

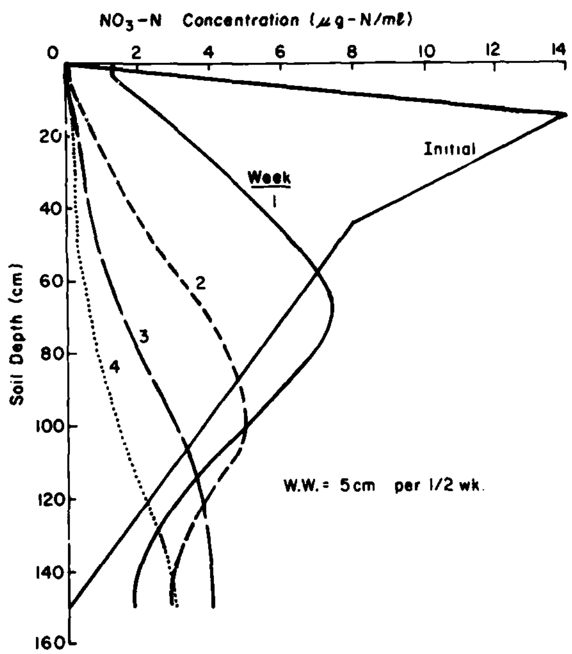

Figure 20. Simulated concentration distributions of NO_3-N in the soil profile where 5 cm of wastewater was applied every ½ week. Model parameters were the same as those used for Figure 10.

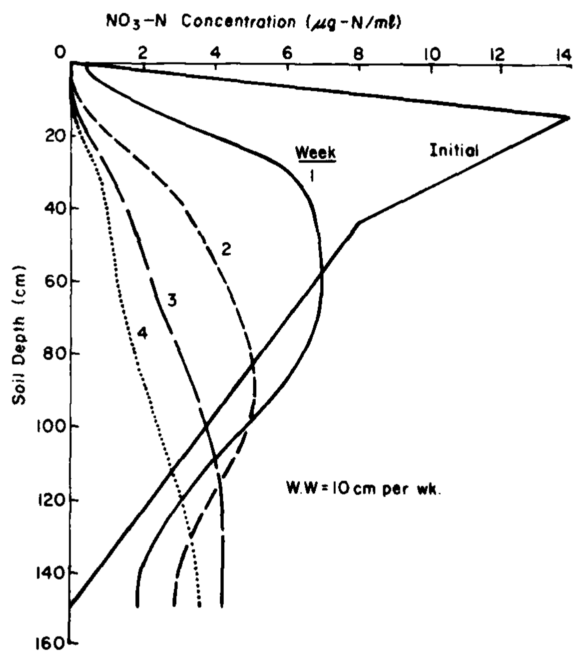

Figure 21. Same as Figure 20 except for weekly application of 10 cm of wastewater.

cumulative nitrogen profile during each application of wastewater. Obviously maximum nitrogen uptake was not met for the cases with I_{max} of 0.001 and 0.0015 μg N/h cm

Figures 20 and 21 show the influence of the amounts and scheduling of wastewater application on nitrate distributions in the soil profile. Figure 20 shows NO_3-N distribution in the soil where 5 cm of wastewater was applied every 3.5 days, i.e. twice weekly. This rate is twice the application rate considered in previous cases where only a 5-cm wastewater application was maintained every week. Figure 21 is for a different case where 10 cm of wastewater is applied in one application every week. All other parameters, for the purpose of

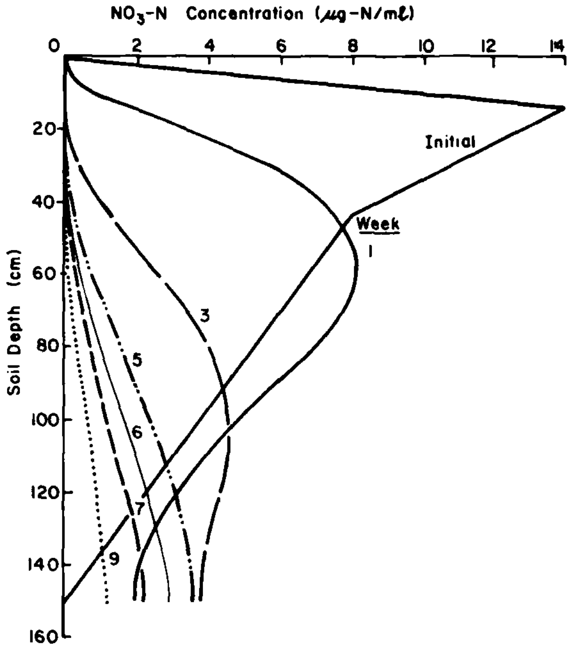

Figure 22. Simulated concentration distributions of NO_3-N in the soil profile where weekly application of 5 cm of wastewater was maintained. Model parameters were the same as those used for Figure 10.

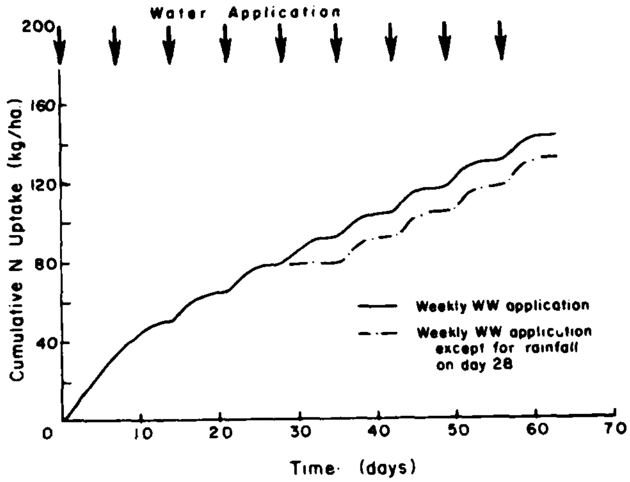

Figure 23. Cumulative N uptake with time where weekly application of 5 cm of wastewater was maintained for a period of 9 weeks. Dashed line is for a case where 5 cm of water (or simulated rainfall), rather than wastewater, was applied on the fifth week (day 28).

comparison, are the same as those used for Figure 10. Comparison of Figures 10 and 20 shows that increasing the schedule of application to 5 cm/½ week, rather than one week, resulted in more leaching of the nitrate nitrogen from the soil profile. In addition, peak concentrations were at lower soil depths when the wastewater was applied twice weekly. Comparison of Figures 20 and 21 shows that the total NO_3-N in the soil was applied once every week than for 5 cm every ½ week. Increased total NO_3-N in the soil profile (shown in Fig. 21) was probably due to increased depth of penetration of NO_3-N in the soil for the 10 cm/week application rate.

The influence of rainfall events on NO_3-N distributions in the soil profile is shown in Figures 22 and 23. Here, we compare a case where 5 cm of wastewater is applied weekly for a total period of 9 weeks to another case where in the fifth week (day 28) 5 cm of water or simulated rainfall containing no NO_3-N or NH_4-N is applied. Figure 22 shows that the results of NO_3-N distributions in the soil for the two cases were identical for the time of simulation considered. This was not surprising since the top portion of the soil profile contained very little NO_3-N at the end of the fourth week. As a result, the effect of the simulated rainfall event on the fifth week was in limiting the amount of N uptake during that time. This is clearly illustrated in Figure 23, where after the fifth week the cumulative N uptake was approximately 125 kg N/ha higher for the case where weekly wastewater was maintained. Moreover, there was a leveling of N uptake during the fifth week for the case where 5 cm of water (or rainfall) was applied on day 28. This difference in the cumulative N uptake between the two cases is equivalent to the total amount of N applied in one wastewater application. These results, therefore, further support the concept that intermittent rainfall, for the cases studied, directly influences the plant uptake rather than NO_3-N distribution in the soil profile. If, however, considerable amounts of NO_3-N are present in the upper portion of the soil profile prior to application of water or simulated rainfall, profiles of NO_3-N vs soil depth different from that shown in Figure 22 would be obtained.

DESCRIPTION OF THE COMPUTER PROGRAM

The computer program that we developed to predict the water and nitrogen transport, transformation, and uptake by plants in the soil profile in land treatment systems is written in FORTRAN language and consists of a SOURCE (or MAIN) program, 10 subroutine programs, three FUNCTION programs, and an input data section. The names of the subroutines are IDIST, IDIST2, ROOTS, INDIDZ, WATER, WPROP, AMONIA, NITRAT, OUTPUT and TRIDM. The names of the function programs are ZZ1, ZZ2, and ZZ3. In addition, the program uses subroutine QSF which is a standard integration subroutine available from the IBM System 360 Scientific Subroutine Package (1970). This subroutine is on file in the CRREL computer system.

Input data section

Unless otherwise stated, the format for the input data is 8F10.3 (see FORMAT 100 in the SOURCE program). The input data which must be provided by the user are as follows:

1. The first record (card) of the data set contains:
   DTT = initial approximation of Δt
   DZZ = initial approximation of Δz (cm)
2. The second record of the data set contains:
   SFLUX = flux v of wastewater application (cm/h)
   ET = evapotranspiration rate T (cm/h)
   QM = I_{max} of the Michaelis-Menten equation for nitrogen uptake (μg/h cm of root length)
   QK = Michaelis constant K_m (μg/ml)
   $CSNH_4$ = concentration of NH_4-N in the wastewater C_s (μg-N/ml)
   $CSNO_3$ = concentration of NO_3-N in the wastewater Y_s (μg-N/ml)
   DISP = solute dispersion coefficient D (cm^2/h)
3. The third record of the input data set contains:
   CL = total length (cm) of the soil profile L
   CL1 = soil depth (cm) to the first soil layer L_1 (see Fig. 1)
   CL2 = soil depth (cm) to the second soil layer L_1+L_2 (see Fig. 1).
4. The fourth record contains soil water parameters for the first soil layer (see *Sensitivity Analysis*). The format used here is E10.4, 6F10.5 (see FORMAT 500 in SOURCE program):
   AC1 = η of eq 37
   BC1 = α of eq 37
   AT1 = a of eq 36
   BT1 = b of eq 36
5. This record is similar to the one above except for the second soil layer.
6. This record is similar to the one above except for the third soil layer.
7. This record contains the soil bulk density (g/cm^3) and saturated water content (cm^3/cm^3) for each soil layer:
   ROU1 = ρ_1, bulk density of the first soil layer
   THS1 = $(\theta_s)_1$, saturated water content of the first soil layer
   ROU2 = ρ_2, bulk density of the second soil layer
   THS2 = $(\theta_s)_2$, saturated water content of the second soil layer
   ROU3 = ρ_3, bulk density of the third soil layer
   THS3 = $(\theta_s)_3$, saturated soil water content of the third soil layer.
8. This record contains the nitrogen parameters for the first soil layers:
   REX1 = $(K_D)_1$, ammonium distribution coefficient (cm^3/g) for the first soil layer.
   RNIT1 = $(k_1)_1$, nitrification rate coefficient (h^{-1}) for the first soil layer.
   RDNIT1 = $(k_2)_1$, denitrification rate coefficient (h^{-1}) for the first soil layer.
9. This record is similar to the one above except for the second soil layer.
10. This record is similar to the one above except for the third soil layer.
11. This record contains:
    TINF = T, duration (h) of wastewater (or rainfall) application
    TCYC = duration of wastewater cycle in hours
    NCYC = number of cycles desired.
12. This record contains:
    TWRITE = time (h) at which output data are requested.

Source program

The main functions of the SOURCE (or main) program are prescribing the DIMENSION statements, reading the input data, and setting up the entire sequence of the program. A detailed flow chart of the SOURCE program is shown in Figure 24.

The DIMENSION statements are introduced in COMMON blocks and are labeled L1 to L18. The array size of most variables is set to be 310. This array size may be changed by the user depending on the depth of the soil profile (L) as well as the incremental distances Δz.

The source program also reads the input parameters and provides the output for these parameters.

The following variables are used in the source program:

C = NH_4-N concentration of soil solution C (μg-N/ml), dimension = NP1.
Y = NO_3-N concentration in soil solution Y (μg-N/ml), dimension = NP1.
H = soil water pressure head h (cm), dimension = NP1.

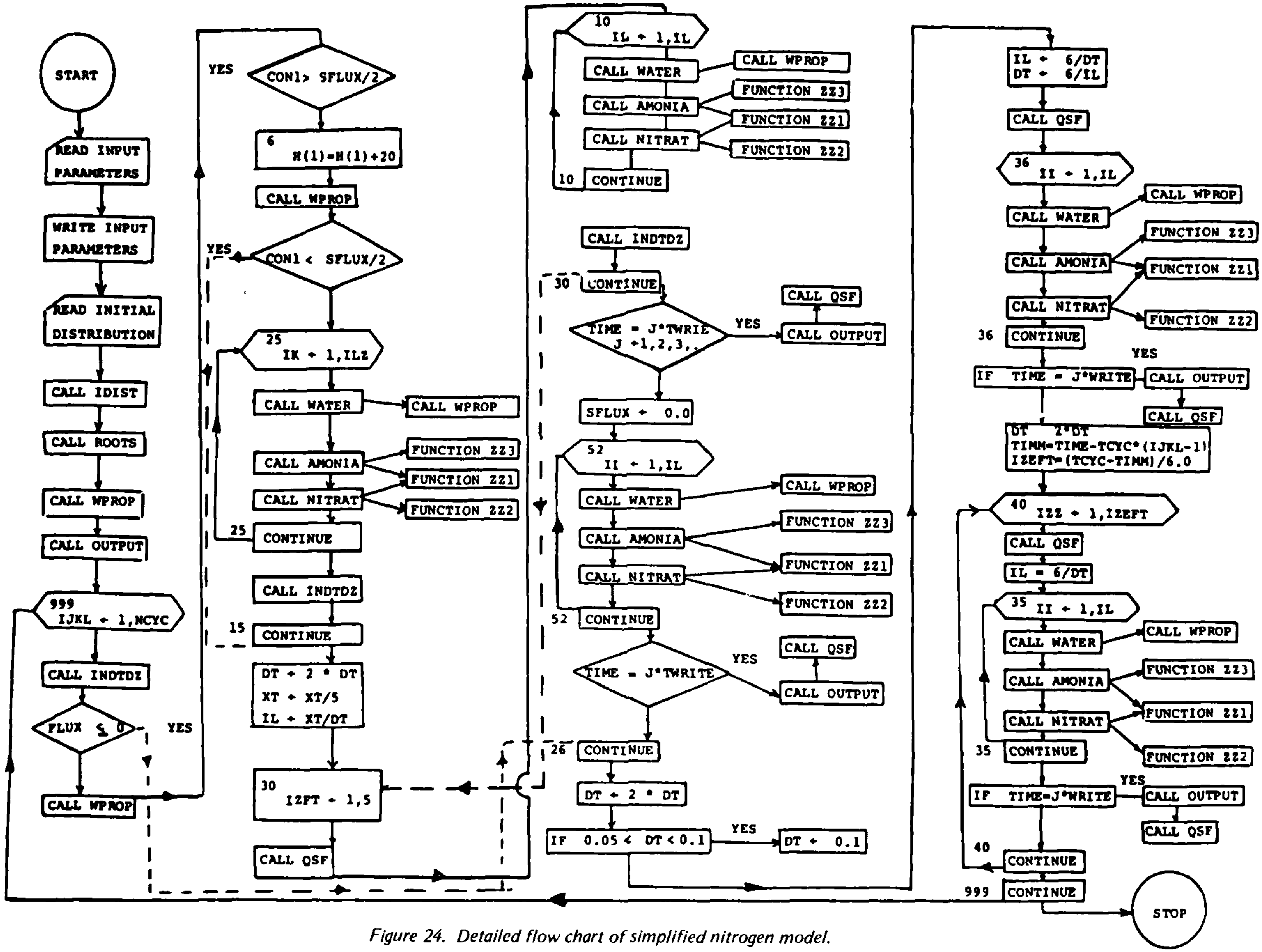

Figure 24. Detailed flow chart of simplified nitrogen model.

TH = soil water content θ (cm^3/cm^3), dimension = NP1.

CON = soil water hydraulic conductivity $K(\theta)$ (cm/h), dimension = NP1.

CAP = soil water capacity Cap (h) (cm^{-1}), dimension = NP1.

RDIST = root density distribution R(z) (cm), dimension = NX

AA, BB, CC, R = dummy variables which are used in solving the matrix-vector equations for water, NH_4-N, and NO_3 -N, dimension = N

XXX = soil depths (cm) for which initial distributions are provided, dimension = NIN

C1 = initial distribution of pressure head (cm) dimension = NIN

C2 = initial distribution of water content (cm^3/cm^3) dimension = NIN

C3 = initial distribution of NH_4-N, (μg-N/ml) dimension = NIN

C4 = initial distribution of NO_3-N, (μg-N/ml), dimension = NIN.

Subroutine IDIST

This subroutine is labeled the "Initial Distribution Program" in the program listing (Appendix A). This subroutine uses the initial input distributions, i.e. initial conditions, at any number of soil depths. In order to calculate the pressure head, water content, NH_4-N and NO_3-N concentration distributions at incremental distances DT (CM) for the entire soil profile the calculations are carried out by linear interpolation using the input data points.

In this subroutine it is not necessary to provide initial water content distributions corresponding to the soil suction for the various soil depths (in input data). Conversion from suction or pressure head to water content is carried out in subroutine WPROP. However, the user must provide some value (zero is recommended) for all input data points.

It should be emphasized here that, if input data for pressure heads, NH_4-4, etc., are not provided for the same soil locations (depths), the user must use subroutine IDIST2.

Subroutine IDIST2

This subroutine is labeled the "Initial Distribution Program Number 2" in the program listing. This subroutine is similar to subroutine IDIST except that it allows the calculation of initial distribution regardless of locations (soil depths) at which measurements are provided. Therefore, this subroutine must be used if initial distributions of all variables (pressure head, NH_4 -H, etc.) are not available at common soil depths.

In this subroutine each variable is treated separately. In addition the number of data points, locations and values of each variable must be supplied in the main program.

Subroutine ROOTS

This subroutine is labeled the " Root Distribution Program" in the program listing. The subroutine provides the root distribution in the soil profile. This root distribution can be expressed as a function of time as well as soil depth in the profile. This is provided as a mathematical expression. In the example below, an exponential decay function of root length with soil depth is used for all times. If desired, the user can express the root distribution as a function of soil depth as well as time.

Subroutine INDTDZ

This subroutine is labeled the "Program for Adjusting Zone of Infiltration" in the program listing. The subroutine may be used only if the water flux in the soil profile is extremely small. In such a case it is reasonable to be mainly concerned with the top portion of the soil profile during the initial stages of wastewater application or rainfall. Such an assumption is applicable if water redistribution continues for several days with no new wastewater application or rainfall. In this program an initial length of 30 cm (root zone) is assumed (N = 30) in the main program. This length is automatically increased during wastewater application. At the termination of infiltration the total length of the profile is incorporated.

It is important to emphasize here that the use of such a subroutine is not essential. However, its use saves a considerable amount of computer time especially during simulation of infiltration when DT is smallest. If this feature is not desirable, the user may ignore it by replacing N = 30 by N = CL/DZ+0.01 in the main program and deleting all call INDTDZ statements.

Subroutine WATER

This subroutine is labeled the "Water Flow Program" in the program listing. The subroutine provides the solution for the water flow equation for a homogeneous or a layered soil profile. The method of solution is based on the finite difference approximations discussed previously. The bottom boundary condition is incorporated in the solution and is applicable for a water table boundary or a semi-infinite (i.e. deep) soil profile. The surface boundary condition (flux type) is provided from main program.

Subroutine WPROP

This subroutine is labeled the "Soil-Water Properties Program" in the program listing. The subroutine

provides the soil-water properties for each soil layer in the soil profile, namely the hydraulic conductivity as a function of water content or suction and the water content–suction relationship. From the latter, the water capacity term is calculated. In this example (see *Sensitivity Analysis*) mathematical expressions are used to describe these relationships. This subroutine is called by subroutine WATER for every time step.

Subroutine AMONIA

This subroutine is labeled the "Ammonium Transport and Transformation Program" in the program listing. The subroutine provides the solution to the ammonium transport and transformation equation under transient flow conditions. It also calculates the ammonium uptake by plant roots. The method of solution is the finite difference approximation method. The rate of nitrification and denitrification and the distribution coefficient for NH_4-N release are obtained from functions ZZ1, ZZ2, and ZZ3, respectively (see below).

Subroutine NITRAT

This subroutine is labeled the "Nitrate Transport of Transformation Program" in the program listing. The subroutine provides the solution to the nitrate transport and transformation equation under transient flow conditions. It also calculates the nitrate uptake by plant roots. The rate of nitrification and denitrification and the distribution coefficient for NH_4-N exchange are obtained from functions ZZ1, ZZ2, and ZZ3, respectively.

Functions ZZ1, ZZ2, ZZ3

Function ZZ1 provides the rate coefficient for nitrification (k_1) for each soil layer. In the example described (see *Sensitivity Analysis*) the rate coefficient was considered dependent on the soil water suction. It was assumed that nitrifying bacteria are present in optimum number and the change in their population during a cycle of wastewater application (most often weekly) is negligible.

Function ZZ2 provides the retardation factor R for ammonium exchange. This is achieved, for each soil layer, from K_D, θ and ρ at incremental soil depths.

All the above functions (ZZ1, ZZ2, and ZZ3) are called by subroutine AMONIA and NITRAT at every time step DT.

Subroutine OUTPUT

The main function of this subroutine is to print the results (output data) at specified times. A second function of this subroutine is to carry out several integration in order to calculate the total amount of NO_3-N and NH_4-N in the soil solution and total NH_4-N in the exchangeable phase.

Subroutine TRIDM

This subroutine is labeled the "Tridiagonal Matrix Program" in the program listing. The subroutine provides the solution of a tridiagonal matrix-vector equation (see text). This subroutine is utilized by subroutine WATER, AMONIA, and NITRAT at every time step DT.

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APPENDIX A: PROGRAM LISTING

```
C***********************************************************************C
C***********************************************************************C
C                                                                       C
C       A  S I M P L I F I E D   M O D E L   F O R   P R E D I C T I O N   C
C                                                                       C
C          O F   N I T R O G E N   B E H A V I O R   I N   L A N D         C
C                                                                       C
C             T R E A T M E N T   O F   W A S T E   W A T E R            C
C                                                                       C
C***********************************************************************C
C                                                                       C
C          THE PURPOSE OF THIS MODEL IS TO PREDICT THE BEHAVIOR OF THE
C     AMMONIUM AND NITRATE NITROGEN SPECIES IN THE SOIL IN LAND TREATMENT  C
C     SYSTEMS..    THE  PROGRAM IS BASED ON THE SOLUTION OF THE TRANSIENT  C
C     WATER FLOW EQUATION SIMULTANEOUSLY WITH THE EQUATIONS DESCRIBING    C
C     THE TRANSPORT , TRANSFORMATIONS, AND UPTAKE OF NITROGEN BY PLANTS.  C
C                                                                       C
C     M A I N   F E A T U R E S :                                       C
C          THE MODEL IS VALID FOR UNIFORM AS WELL AS MULTILAYERED SOIL   C
C     PROFILES.   IN ADDITION,  THE PROGRAM IS FLEXIBLE AND IS DESIGNED   C
C     TO INCORPORATE THE FOLLOWING (INPUT) CONDITIONS AS DESIRED ;       C
C                      1.    RATE OF WASTE WATER APPLICATION            C
C                      2.    DURATION OF WASTE WATER APPLICATION        C
C                      3.    DEPTH OF INDIVIDUAL SOIL LAYERS            C
C                      4.    CONCENTRATION OF AMMONIUM AND NITRATE IN THE  C
C                            WASTE WATER                                C
C                      5.    WASTE WATER APPLICATION CYCLE,  I.E.  SCHEDULING  C
C                      6.    SOIL WATER PROPERTIES AND NITROGEN TRANSFORMATION  C
C                            MECHANISMS FOR INDIVIDUAL SOIL LAYERS      C
C                      7.    PLANT ROOT DISTRIBUTION AND GROWTH IN THE SOIL  C
C                      8.    RATE OF NITROGEN UPTAKE BY PLANTS          C
C                      9.    EVAPOTRANSPIRATION RATE
C                     10.    INITIAL DISTRIBUTION OF WATER AND NITROGEN  C
C                            SPECIES IN THE SOIL PROFILE                C
C***********************************************************************C
C
      COMMON/L1/   C(310),Y(310)
      COMMON/L2/ AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L5/   NX,NX1,NRMAX,CON1
      COMMON/L6/   FLNH4,FLNO3,DNITRF
      COMMON/L7/   SFLUX,ET,QM,QK,CSNH4,CSNO3,DISP,XL
      COMMON/L8/   XXX(30),C1(30),C2(30),C3(30),C4(30),NIN
      COMMON/L9/   TIME,TINF,TCYC
      COMMON/L10/  H(310),CON(310),CAP(310),TH(310)
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L12/  AC1,BC1,AT1,BT1
      COMMON/L13/  AC2,BC2,AT2,BT2
      COMMON/L14/  AC3,BC3,AT3,BT3
      COMMON/L15/  ROU1,THS1,ROU2,THS2,ROU3,THS3
      COMMON/L16/  REX1,RNIT1,RDNIT1
      COMMON/L17/  REX2,RNIT2,RDNIT2
      COMMON/L18/  REX3,RNIT3,RDNIT3
  100 FORMAT(8F10.3)
  101 FORMAT(5X,'INITIAL DT, HR =',F10.5/,5X,'INITIAL DZ , CM=',F10.5//)
  200 FORMAT(2F10.5,I3)
  300 FORMAT(2I4)
```

```
600  FORMAT(10E12.4)
500  FORMAT(E10.4,6F10.5)
105  FORMAT(5X,'FLUX OF WASTE WATER APPLICATION,  CM/ HR =',F10.5/,
    *5X,'EVAPOTRANSPIRATION RATE, CM/HR =',F10.5/,
    $5X,'NITROGEN UPTAKE RATE, MICROGRAM-N/CM OF ROOT LENGTH PER HOUR',
    $' =',F10.5/,
    *5X,'MICHAELIS CONSTANT =',F10.5/,
    $5X,'CONCENTRATION OF APPLIED NH4-N , MG/LITRE =',F10.5/,
    *5X,'CONCENTRATION OF APPLIED NO3-N , MG/LITRE =',F10.5/,
    $5X,'SOLUTE DISPERSION COEFFICIENT, CM**2/HR =',F10.5/)
110  FORMAT(5X,'TOTAL LENGTH OF SOIL PROFILE, CM =',F10.5/,
    *5X,'SOIL DEPTH TO THE FIRST SOIL LAYER, CM =',F10.5/,
    $5X,'SOIL DEPTH TO THE SECOND SOIL LAYER, CM =',F10.5/)
115  FORMAT(5X,'SOIL WATER PARAMETERS FOR THE FIRST  LAYER :',4E15.4)
120  FORMAT(5X,'SOIL WATER PARAMETERS FOR THE SECOND LAYER :',4E15.4)
125  FORMAT(5X,'SOIL WATER PARAMETERS FOR THE THIRD  LAYER :',4E15.4)
130  FORMAT(5X,
    *'FIRST LAYER  ;  BULK DENSITY =',F10.5,10X,'SATURATION =',F10.5/,
    *5X,
    *'SECOND LAYER ;  BULK DENSITY =',F10.5,10X,'SATURATION =',F10.5/,
    *5X,
    *'THIRD  LAYER ;  BULK DENSITY =',F10.5,10X,'SATURATION =',F10.5/,
    *5X)
135  FORMAT(5X,'FIRST LAYER:',10X,'NH4-N EXCHANGEABLE COEFFICIENT, CM3/
    *GM =',F10.5/,26X,'NITRIFICATION RATE COEF.,HR-1 =',F10.5/,26X,
    *'DENITRIFICATION RATE COEF., HR-1 =',F10.5)
140  FORMAT(5X,'SECOND LAYER',10X,'NH4-N EXCHANGEABLE COEFFICIENT, CM3/
    *GM =',F10.5/,26X,'NITRIFICATION RATE COEF.,HR-1 =',F10.5/,26X,
    *'DENITRIFICATION RATE COEF., HR-1 =',F10.5)
145  FORMAT(5X,'THIRD LAYER:',10X,'NH4-N EXCHANGEABLE COEFFICIENT, CM3/
    *GM =',F10.5/,26X,'NITRIFICATION RATE COEF.,HR-1 =',F10.5/,26X,
    *'DENITRIFICATION RATE COEF., HR-1 =',F10.5)
150  FORMAT(5X,'DURATION OF WASTE WATER APPLICATION , HRS =',F10.5/,5X,
    *'SCHEDULE OF WASTE WATER APPLICATION, I.E. CYCLE DURATION =',
    $F10.5/,5X,'NUMBER OF CYCLES =',I3/)
155  FORMAT(5X,'TIME AT WHICH OUTPUT DATA IS REQUESTED,HR =',F10.5/)
160  FORMAT(I25,'I N P U T   D A T A',///)
165  FORMAT('1')
     WRITE(6,160)
     READ(5,100)   DTT,DZZ
     WRITE(6,101)  DTT,DZZ
     READ(5,100)   SFLUX,ET,QM,CK,CSNH4,CSNO3,DISP
     WRITE(6,105)  SFLUX,ET,QM,CK,CSNH4,CSNO3,DISP
     READ(5,100)   CL,CL1,CL2
     WRITE(6,110)  CL,CL1,CL2
     READ(5,500)   AC1,BC1,AT1,BT1
     WRITE(6,115)  AC1,BC1,AT1,BT1
     READ(5,500)   AC2,BC2,AT2,BT2
     WRITE(6,120)  AC2,BC2,AT2,BT2
     READ(5,500)   AC3,BC3,AT3,BT3
     WRITE(6,125)  AC3,BC3,AT3,BT3
     READ(5,100)   ROU1,THS1,ROU2,THS2,ROU3,THS3
     WRITE(6,130)  ROU1,THS1,ROU2,THS2,ROU3,THS3
     READ(5,100)   REX1,RNIT1,RDNIT1
     WRITE(6,135)  REX1,RNIT1,RDNIT1
     READ(5,100)   REX2,RNIT2,RDNIT2
     WRITE(6,140)  REX2,RNIT2,RDNIT2
     READ(5,100)   REX3,RNIT3,RDNIT3
```

```
      WRITE(6,145)  REX3,RNIT3,RDNIT3
      READ(5,200)   TINF,TCYC,NCYC
      WRITE(6,150)  TINF,TCYC,NCYC
      READ(5,100)   TWRITE
      WRITE(6,155)  TWRITE
C
      PLNO3=0.0
      PLNH4=0.0
      DNITRF=0.0
C
      DT=DTT
      DZ=DZZ
      WFLX=SFLUX
C
      NKK=TWRITE+0.10
      N=CL/DZ+0.10
      L1=CL1/DZ+0.10
      L2=CL2/DZ+0.10
      NM1=N-1
      NM2=N-2
      NP1=N+1
      NP2=N+2
C
      ICL=CL/DZ+0.10
      ICL=ICL+1
C
C
C     READ NUMBER (INTEGER) OF DATA POINTS FOR WHICH INITIAL DISTRIBUTIONS
C     ARE PROVIDED
C     READ(5,300) NIN
C          READ SOIL DEPTHS FOR INITIAL DISTRIBUTION
C     READ(5,100)   (XXX(I),I=1,NIN)
C          READ PRESSIRE HEAD FOR INITIAL DISTRIBUTION
C     READ(5,100)   (C1(I),I=1,NIN)
C          READ WATER CONTENT FOR INITIAL DISTRIBUTION       (IF AVAILABLE)
C     READ(5,100)   (C2(I),I=1,NIN)
C          READ NH4-N CONCEN, FOR INITIAL DISTRIBUTION
C     READ(5,100)   (C3(I),I=1,NIN)
C          READ NO3-N CONCEN, FOR INITIAL DISTRIBUTION
C     READ(5,100)   (C4(I),I=1,NIN)
C
C     CALL IDIST
C
C
C
C     IF ALL VARIABLES ( I.E. PRESSURE HEAD, NH4-N CONC. ETC.) ARE NOT
C     AVILABLE AT COMMON SOIL DEPTHS,  SUBROUTINE IDIST2 MUST BE USED.
C     READ NUMBER OF DATA POINTS FOR PRESSURE HEADS
      READ(5,300) NIN
C     READ SOIL DEPTH (LOCATIONS) FOR PRESSURE HEADS
      READ(5,100)   (XXX(I),I=1,NIN)
C     READ PRESSURE HEAD FOR CORRESPONDING DEPTHS
      READ(5,100)   (C1(I),I=1,NIN)
      CALL IDIST2
      DO  11  I=1,NP1
   11 H(I)=R(I)
C     READ NUMBER OF DATA POINTS FOR WATER CONTENT  (IF AVAILABLE)
      READ(5,300) NIN
```

```
C       READ SOIL DEPTH (LOCATIONS) FOR WATER CONTENT
        READ(5,100)   (XXX(I),I=1,NIN)
C       READ WATER CONTENT FOR CORRESPONDING DEPTHS
        READ(5,100)   (C1(I),I=1,NIN)
        CALL IDIST2
        DO  12  I=1,NP1
   12   TH(I)=R(I)
C       READ NUMBER OF DATA POINTS FOR NH4-N CONCENTRATION
        READ(5,300) NIN
C       READ SOIL DEPTH (LOCATIONS) FOR NH4-N CONCENTRATION
        READ(5,100)   (XXX(I),I=1,NIN)
C       READ NH4-N CONCEN. FOR CORRESPONDING DEPTHS
        READ(5,100)   (C1(I),I=1,NIN)
        CALL IDIST2
        DO  13  I=1,NP1
   13   C(I)=R(I)
C       READ NUMBER OF DATA POINTS FOR NO3-N CONCENTRATION
        READ(5,300) NIN
C       READ SOIL DEPTH (LOCATIONS) FOR NO3-N CONCENTRATION
        READ(5,100)   (XXX(I),I=1,NIN)
C       READ NO3-N CONCEN. FOR CORRESPONDING DEPTHS
        READ(5,100)   (C1(I),I=1,NIN)
        CALL IDIST2
        DO  14  I=1,NP1
   14   Y(I)=R(I)
C
C
        CALL ROOTS
        CALL WPROP
        CALL OUTPUT
        WRITE(6,165)
C
        TIME=0.0
        XTINF=TINF
        DO  999  IJKL=1,NCYC
        TINF=TIME+XTINF
        DT=DTT
        DZ=DZZ
        SFLUX=WFIX
C
        N=30
        NX=N
        CALL INDTDZ
        NX1=NX-1
C
        IF(SFLUX.LE.0.0) GO TO 26
        TTT=4.0/(SFLUX*1000.0)
        IF(DT.LE.TTT) GO TO 5
        NT=DT/TTT+0.10
        DT=DT/NT
    5   CONTINUE
        ALPHA=DT/(2.0*DZ*DZ)
        BETA=DT/DZ
C
        CALL WPROP
        IF(CON1.GE.(SFLUX/2)) GO TO 15
C
    6   H(1)=H(1)+20
```

```
      CALL WPROP
      IF(CON1.LT.(SFLUX/2)) GO TO 6
      IF(H(1).GT.0.0) H(1)=0.0
      H(1)=H(1)-60.0
C
      XL=1000.0
      DELH=2.0
  7   CONTINUE
      ILZ=30
      DO  25  IK=1,ILZ
      CALL WATER
      CALL AMONIA
      CALL NITRAT
      H(1)=H(1)+DELH
   25 CONTINUE
      TIME=TIME+DT*ILZ
      CALL INDTDZ
C
  15  CONTINUE
C
      DT=DT*2.0
      ALPHA=DT/(2.0*DZ*DZ)
      BETA=DT/DZ
      XI=TINF-TIME
      XT=XI/5
      IL=XT/DT+0.010
      DO  30  IZFT=1,5
      DO  17  I=1,NX
  17  AA(I)=EDIST(I)*CON(I)
      CALL QSF(DZ,AA,R,NX)
      XL=R(NX)
      DO  10 II=1,IL
      ADJ=DZ*(1.0-SFLUX/CON1)
      H(1)=H(2)-ADJ
      CALL WATER
      CALL AMONIA
      CALL NITRAT
   10 CONTINUE
      TIME=TIME+IL*DT
      CALL INDTDZ
  30  CONTINUE
      KK=TIME+0.050
      J=KK-NKK*(KK/NKK)
      IF(J.EQ.0) CALL OUTPUT
      SFLUX=0.0
      TN=6.0+TCYC*(IJKL-1)
 53   IF((TN-TINF).GT.1.0) GO TO 54
      TN=TN+6.0
      GO TO 53
  54  IL=(TN-TIME)/DT+0.010
      DT=(TN-TIME)/IL
C
C
      DO  31  I=1,NX
  31  AA(I)=EDIST(I)*CON(I)
      CALL QSF(DZ,AA,R,NX)
      XL=R(NX)
      DO  52  II=1,IL
```

```
      ADJ=DZ*(1.0-SFLUX/CON1)
      H(1)=H(2)-ADJ
      CALL WATER
      CALL AMONIA
      CALL NITRAT
 52   CONTINUE
      TIME=TIME+IL*DT
      CALL INDTDZ
      KK=TIME+0.050
      J=KK-NKK*(KK/NKK)
      IF(J.EQ.0) CALL OUTPUT
C
C
 26   CONTINUE
C
      DT=DT*2
      IF(DT.GT.0.050.AND.DT.LT.0.10)   DT=0.10
      ALPHA=DT/(2.0*DZ*DZ)
      BETA=DT/DZ
      IL=6.00/DT+0.010
      DT=6.0/IL
C
      DO   34   I=1,NX
 34   AA(I)=RDIST(I)*CON(I)
      CALL CSF(DZ,AA,R,NX)
      XL=R(NX)
      DO   36 II=1,IL
      ADJ=DZ*(1.0-SFLUX/CON1)
      H(1)=H(2)-ADJ
      CALL WATER
      CALL AMONIA
      CALL NITRAT
 36   CONTINUE
      TIME=TIME+IL*DT
      KK=TIME+0.050
      J=KK-NKK*(KK/NKK)
      IF(J.EQ.0) CALL OUTPUT
C
      DT=2*DT
      IF(DT.GT.0.050.AND.DT.LT.0.10)   DT=0.10
      IF(DT.GT.0.190.AND.DT.LT.0.40)   DT=0.250
C
      ALPHA=DT/(2.0*DZ*DZ)
      BETA=DT/DZ
C
      TIMM=TIME-TCYC*(IJKL-1)
      IZEFT=(TCYC-TIMM)/6.0
      DO   40   IZZ=1,IZEFT
      IL=6.00/DT+0.010
      DT=6.0/IL
      DO   18   I=1,NX
 18   AA(I)=LDIST(I)*CON(I)
      CALL CSF(DZ,AA,R,NX)
      XL=R(NX)
      DO   35 II=1,IL
      ADJ=DZ*(1.0-SFLUX/CON1)
      H(1)=H(2)-ADJ
      CALL WATER
```

```
      CALL AMONIA
      CALL NITRAT
   35 CONTINUE
      TIME=TIME+IL*DT
      KK=TIME+0.050
      J=KK-NKK*(KK/NKK)
      IF(J.EQ.0) CALL OUTPUT
      DT=2*DT
      IF(DT.GT.2.0) DT=2.0
      ALPHA=DT/(2*DZ*DZ)
      BETA=DT/DZ
   40 CONTINUE
C     IF ANY CHANGES IN INPUT DATA ( ESPECIALLY THE BOUNDARY CONDITIONS)
C     ARE REQUIRED IN THE CYCLE, THE INPUTS SHOULD BE ENTERED HERE
C     FOR EXAMPLE NEW FLUX, EVAPOTRANSPIRATION RATE, DURATION OF WASTE
C     WATER APPLICATION, CYCLE DURATION, CONCENTRATION OF NH4-N, AND
C     NO3-N MAY BE ENTERED AS FOLLOWS.
C     READ(5,100) SFLUX, ET,TINF,TCYC,CSNH4,CSNO3
C     P.S.      RAINFALL EVENTS CAN BE TREATED AS A CYCLE BY ENTERING ZERO
C     VALUES FOR APPLIED NH4-N AND NO3-N AS WELL AS PROVIDING THE PROPER
C     INPUTS FOR FLUX (INTENSITY),DURATION OF RAINFALL AS WELL AS THE
C     TOTAL TIME BEFORE THE NEW WASTE WATER APPLICATION BEGINS (TCYC)
C     WARNING:
C               IF THE ABOVE IS DESIRABLE  THEN    NEW DATA FOR EACH
C               SUBSEQUENT CYCLE MUST BE PROVIDED
  999 CONTINUE
C
      STOP
      END
```

```
C***********************************************************************C
C                                                                       C
C     I N I T I A L     D I S T R I B U T I O N     P R O G R A M
C                                                                       C
C     THIS SUBROUTINE UTILIZES THE INITIAL INPUT DISTRIBUTIONS ,I.E.    C
C     INITIAL CONDITIONS, AT ANY NUMBER OF SOIL DEPTHS IN THE SOIL,     C
C     IN ORDER TO CALCULATE THE PRESSURE HEAD, WATER CONTENT, NH4-N     C
C     AND NO3-N CONCENTRATION DISTRIBUBIONS AT INCREMENTAL DISTANCES DZ C
C     (CM) FOR THE ENTIRE SOIL PROFILE.  IN  THIS  PROGRAM              C
C     THE CALCULATIONS ARE CARRIED OUT USING LINEAR INTERPOLATION       C
C     USING THE INPUT DATA POINTS.                                      C
C     IMPORTANT:                                                        C
C              IN THIS PROGRAM IT IS NOT NECESSARY TO PROVIDE INITIAL   C
C              WATER CONTENT DISTRIBUTIONS CORRESPONDING TO THE SOIL    C
C              SUCTION FOR THE VARIOUS SOIL DEPTH (IN INPUT DATA ).     C
C              CONVERSION FROM SUCTION OR PRESSURE HEAD TO WATER CONTENT C
C              IS CARRIED OUT IN SUPROUTINE WPROP  HOWEVER, THE USER    C
C              MUST PRIVIDE SOME VALUE(ZERO IS RECOMMENDED) FOR ALL     C
C              INPUT DATA POINTS                                        C
C                                                                       C
C                W A R N I N G
C      IF  INPUT  DATA  FOR PRESSURE HEADS, NH4-N, ETC. ARE NOT PROVIDED C
C      FOR THE SAME  SOIL LOCATIONS (DEPTHS)  THE USER MUST USE         C
C      SUBROUTINE IDIST2                                                C
C
C***********************************************************************C
C                                                                       C
      SUBROUTINE IDIST
      COMMON/L1/   C(310),Y(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L8/   XXX(30),C1(30),C2(30),C3(30),C4(30),NIN
      COMMON/L10/  H(310),CON(310),CAP(310),TH(310)
      COMMON/L11/  CL,CL1,CL2,L1,L2
  100 FORMAT(8F10.4)
      I=1
      DO  20  K=1,NP1
      A=DZ*(K-1)
    5 IF(A.LE.XXX(I+1)) GO TO 10
      I=I+1
      GO TO 5
   10 H(K)=C1(I)+(A-XXX(I))*((C1(I+1)-C1(I))/(XXX(I+1)-XXX(I)))
      TH(K)=C2(I)+(A-XXX(I))*((C2(I+1)-C2(I))/(XXX(I+1)-XXX(I)))
      C(K)=C3(I)+(A-XXX(I))*((C3(I+1)-C3(I))/(XXX(I+1)-XXX(I)))
      Y(K)=C4(I)+(A-XXX(I))*((C4(I+1)-C4(I))/(XXX(I+1)-XXX(I)))
   20 CONTINUE
      RETURN
      END
```

```
C*****************************************************************************C
C                                                                             C
C     I N T I A L     D I S T R I B U T I O N      P R O G R A M   NO. 2      C
C                                                                             C
C*****************************************************************************C
C                                                                             
C         THIS SUBROUTINE IS SIMILAR TO SUBROUTINE IDIST EXCEPT THAT         C
C     IT ALLOWS THE CALCULATION OF INITIAL DISTRIBUTION REGARDLESS OF        C
C     LOCATIONS (SOIL DEPTHS) AT WHICH MEASUREMENTS ARE PROVIDED.            C
C     THEREFORE,  THIS SUBROUTINE MUST BE USED IF INITIAL DISTRIBUTIONS      C
C     OF ALL VARIABLES  ( PRESSURE HEAD, NH4-N, ETC.)  ARE NOT AVAILABLE AT  C
C     COMMON SOIL DEPTHS.                                                     C
C     IMPORTANT:                                                              C
C                EACH VARIABLE IS TREATED SEPERATLY.  IN ADDITION THE         C
C                NUMBER OF DATA POINTS, LOCATIONS AND VALUES OF EACH          C
C                VARIABLE MUST BE SUPPLIED IN THE MAIN PROGRAM.               C
C                                                                             C
C*****************************************************************************C
C
      SUBROUTINE IDIST2
      COMMON/L2/ AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L8/   XXX(30),C1(30),C2(30),C3(30),C4(30),NIN
      I=1
      DO  20  K=1,NP1
      A=DZ*(K-1)
    5 IF(A.LE.XXX(I+1)) GO TO 10
      I=I+1
      GO TO 5
   10 R(K)=C1(I)+(A-XXX(I))*((C1(I+1)-C1(I))/(XXX(I+1)-XXX(I)))
   20 CONTINUE
      RETURN
      END

C*****************************************************************************C
C                                                                             C
C     R O O T      D I S T R I B U T I O N      P R O G R A M                 C
C                                                                             C
C     THIS SUBROUTINE PROVIDES THE ROOT DISTRIBUTION IN THE SOIL PROFILE.     C
C     THIS ROOT DISTRIBUTION CAN BE EXPRESSED AS A FUNCION OF TIME AS         C
C     WELL  AS SOIL DEPTH IN THE PROFILE.                                     C
C     THIS MAY MAY PROVIDED AS A MATHEMATICAL EXPRESSION.                     C
C     IN THE EXAMPLE BELOW AN EXPONENTIAL DECAY  FUNCTION OF ROOT LENGTH      C
C     WITH SOIL DEPTH IS USED  FOR ALL TIMES.                                 C
C     IMPORTANT:                                                              C
C                 ROOT DISTRIBUTION IS EXPRESSED IN TERMS OF TOTAL ROOT       C
C                 LENGTH PER UNIT BULK  VOLUME OF SOIL.                       C
C*****************************************************************************C
      SUBROUTINE ROOTS
      COMMON/L2/   AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L5/   NX,NX1,NRMAX,CON1
      COMMON/L9/   TIME,TINF,TCYC
C     MATHEMATICAL EXPRESSION OF ROOT LENGTH AS A FUNCTION
C     OF SOIL DEPTH
      DO  5  I=1,N
      Z=(I-1)*DZ
    5 RDIST(I)=226.0*EXP(-0.100*Z)
C
      NX=60
   10 CT=RDIST(NX)/RDIST(1)
      IF(CT.LT.0.010) GO TO 15
      NX=NX+10
      GO TO 10
   15 NX1=NX-1
      NRMAX=NX
      RETURN
      END
```

```
C*****************************************************************************C
C                                                                             C
C        P R C G R A M   F O R   A D J U S T I N G   Z O N E                  C
C                                                                             C
C                  O F   I N F I L T R A T I O N                              C
C                                                                             C
C*****************************************************************************C
C
C     THIS SUBROUTINE  MAY BE USED ONLY IF THE WATER FLUX IN THE SOIL         C
C     PROFILE IS EXTREMELY SMALL.    IN SUCH A CASE IT IS REASONABLE TO       C
C     BE MAINLY CONCERNED WITH THE TOP PORTCON OF THE SOIL PROFILE DURING     C
C     THE INITIAL STAGES OF WASTE WATER APPLICATION OR RAINFALL.              C
C     SUCH AN ASSUMPTION IS APPLICABLE IF  WATER REDISTRIBUTION CONTINUES     C
C     FOR SEVERAL DAYS WITH NO NEW WASTE WATER APPLICATICN OR RAINFALL.       C
C     IN THIS PROGRAM AN INITIAL LENGTH OF 30 CM IS ASSUMED (N = 30).         C
C     THIS LENGTH IS AUTOMATICALLY INCREASED DURING WASTE WATER APPLICATION.  C
C     AT THE TERMINATION OF INFITRATION THE TOTAL LENGTH OF THE PROFILE IS    C
C     INCCRPORATED.                                                           C
C     IMPORTANT:                                                              C
C              THE USE OF SUCH A SUBROUTINE IS NOT NESESSARY.                 C
C              HOWEVER IT SAVES A CONSIDERAVLE AMOUNT OF COMPUETER TIME        C
C              DURING SIMULATION OF INFILTRATION WHEM DT IS SMALLEST          C
C              IF THIS FEATURE IS NOT DESIRABLE THE USER MAY IGNORE           C
C              IT BY REPLACING N = 30 BY N=CL/DZ+0.01  IN THE MAIN            C
C              PRCGRAM AND DELETING ALL CALL INDTDZ STATEMENTS                C
C*****************************************************************************C
C
      SUBROUTINE INDTDZ
      COMMON/L3/    N,NM1,NM2,NP1,NP2
      COMMON/L4/    ALPHA,BETA,DT,DZ
      COMMON/L5/    NX,NX1,NRMAX,CON1
      COMMON/L9/    TIME,TINF,TCYC
      COMMON/L11/  CL,CL1,CL2,L1,L2
      N=N+10
      IF(TIME.GE.TINF) N=CL/DZ+0.10
      NM1=N-1
      NM2=NM2
      NP1=N+1
      NP2=N+2
      NX=NX+10
      IF(NX.GT.NRMAX) NX=NRMAX
      NX1=NX-1
      RETURN
      END
```

```
C*************************************************************************C
C                                                                         C
C              W A T E R    F L O W    P R O G R A M                      C
C                                                                         C
C*************************************************************************C
C
C      THIS SUBROUTINE PROVIDES THE SOLUTION FOR THE WATER FLOW EQUATION  C
C      FOR A HOMOGENEOUS   OR                                             C
C      FOR A LAYERED SOIL PROFILE                                         C
C      THE METHOD OF SOLUTION IS BASED ON FINITE DIFFERENCE APPROXIMATION C
C      ( SEE TEXT )                                                       C
C      THE BOTTOM BOUNDARY CONDITION IS INCORPORATED IN THE SOLUTION      C
C      AND IS APPLICABLE FOR A WATER TABLE BOUNDARY OR A SEMI - INFINITE  C
C      (I.E. DEEP) SOIL  PROFILE                                          C
C      THE SURFACE BOUNDARY CONDITION ( FLUX BOUNDARY CONDITION ) IS      C
C      PROVIDED FROM MAIN PROGRAM.                                        C
C                                                                         C
C*************************************************************************C
C
      SUBROUTINE WATER
      COMMON/L1/   C(310),Y(310)
      COMMON/L2/   AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L5/   NX,NX1,NRMAX,CON1
      COMMON/L6/   PLNH4,PLNO3,DNITRF
      COMMON/L7/   SFLUX,ET,QM,QK,CSNH4,CSNO3,DISP,XL
      COMMON/L8/   XXX(30),C1(30),C2(30),C3(30),C4(30)
      COMMON/L9/   TIME,TINF,TCYC
      COMMON/L10/  H(310),CON(310),CAP(310),TH(310)
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L12/  AC1,BC1,AT1,BT1
      COMMON/L13/  AC2,BC2,AT2,BT2
      COMMON/L14/  AC3,BC3,AT3,BT3
      COMMON/L15/  ROU1,THS1,ROU2,THS2,ROU3,THS3
      COMMON/L16/  REX1,RNIT1,RDNIT1
      COMMON/L17/  REX2,RNIT2,RDNIT2
      COMMON/L18/  REX3,RNIT3,RDNIT3
      CALL WPROP
C
      DO  1  I=1,NM1
      AA(I)=CAP(I+1)+ALPHA*(CON(I+1)+CON(I))
      BB(I)=-ALPHA*CON(I+1)
      CC(I)=-ALPHA*CON(I+1)
    1 CONTINUE
      DO 2 I=1,NM1
      X1=CAP(I+1)*H(I+1)
      X2=ALPHA*CON(I)*H(I)-ALPHA*H(I+1)*(CON(I+1)+CON(I))
      X3=ALPHA*CON(I+1)*H(I+2)
      X4=-BETA*(CON(I+1)-CON(I))
      R(I)=X1+X2+X3+X4
    2 CONTINUE
      R(1)=R(1)+ALPHA*CON(1)*H(1)
      R(NM1)=R(NM1)-BB(NM1)*H(NP1)
      DO   5   I=1,NX1
      X5=-DT*ET*CON(I+1)*RDIST(I+1)/XL
      C(I)=C(I)*TH(I)/(TH(I)+X5)
      Y(I)=Y(I)*TH(I)/(TH(I)+X5)
      R(I)=R(I)+X5
  5   CONTINUE
      CALL TRIDM(AA,BB,CC,R,NM1)
      DO 3 K=2,N
   3  H(K)=R(K-1)
      RETURN
      END
```

```
C*********************************************************************C
C                                                                     C
C        S O I L - W A T E R   P R O P E R T I E S   P R O G R A M    C
C                                                                     C
C*********************************************************************C
C                                                                     C
C     THIS SUBROUTINE PROVIDES THE SOIL-WATER PROPERTIES FOR EACH SOIL C
C     LAYER IN THE SOIL PROFILE NAMELY THE HYDRAULIC CONDUCTIVITY AS   C
C     A FUNCTION OF WATER CONTENT OR SUCTION AND THE WATER CONTENT - SUCTION C
C     RELATIONSHIP.  FROM THE LATTER, THE WATER CAPACITY TERM IS CALULATED C
C     IN THIS EXAMPLE MATHEMATICAL EXPRESSIONS ARE USED TO DESCRIBE THESE C
C     SOIL WATER PROPERTIES FOR INDIVIDUAL SOIL LAYERS (SEE TEXT ).    C
C*********************************************************************C
C
      SUBROUTINE WPROP
      COMMON/L2/ AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L5/   NX,NX1,NRMAX,CON1
      COMMON/L10/  H(310),CON(310),CAP(310),TH(310)
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L12/  AC1,BC1,AT1,BT1
      COMMON/L13/  AC2,BC2,AT2,BT2
      COMMON/L14/  AC3,BC3,AT3,BT3
      COMMON/L15/  ROU1,THS1,ROU2,THS2,ROU3,THS3
      DO  90  I=1,L1
      R(I)=H(I)
      IF(R(I).GT.0.0)  R(I)=0.0
      XX=THS1*(1.0+(-R(I)/AT1))**(-2)
      CAP(I)=XX/AT1
      TH(I)=THS1/(1.0+(-R(I)/AT1))
      CON(I)=AC1*EXP(BC1*(TH(I)+TH(I+1))/2)
   90 CONTINUE
      I=L1
      CON(I)=AC1*EXP(BC1*TH(I))
      LI=L1+2
      DO  92  I=LI,L2
      R(I)=H(I)
      IF(R(I).GT.0.0)  R(I)=0.0
      XX=THS2*(1.0+(-R(I)/AT2))**(-2)
      CAP(I)=XX/AT2
      TH(I)=THS2/(1.0+(-R(I)/AT2))
      CON(I)=AC2*EXP(BC2*(TH(I)+TH(I+1))/2)
   92 CONTINUE
C
      I=L2
      CON(I)=AC2*EXP(BC2*TH(I))
C
      I=NP1
      R(I)=H(I)
      IF(R(I).GT.0.0)  R(I)=0.0
      XX=THS3*(1.0+(-R(I)/AT3))**(-2)
      CAP(I)=XX/AT3
      TH(I)=THS3/(1.0+(-R(I)/AT3))
      CON(I)=AC3*EXP(BC3*TH(I))
C
      LII=L2+2
      DO  93  I=LII,N
      R(I)=H(I)
```

```
      IF(R(I).GT.0.0)  R(I)=0.0
      TH(I)=THS3/(1.0+(-R(I)/AT3))
      CAP(I)=XX/AT3
      XX=THS3*(1.0+(-R(I)/AT3))**(-2)
      CON(I)=AC3*EXP(BC3*(TH(I)+TH(I+1))/2)
   93 CONTINUE
      I=L1+1
      TH(I)=(TH(I-1)+TH(I+1))/2
      CON(I)=(CON(I-1)+CON(I+1))/2
      CAP(I)=(CAP(I-1)+CAP(I+1))/2
      I=L2+1
      TH(I)=(TH(I-1)+TH(I+1))/2
      CON(I)=(CON(I-1)+CON(I+1))/2
      CAP(I)=(CAP(I-1)+CAP(I+1))/2
C
      CON1=AC1*EXP(BC1*TH(1))
      RETURN
      END
C***************************************************************************C
C                                                                           C
C        N I T R I F I C A T I O N    R A T E    P R O G R A M             C
C                                                                           C
C***************************************************************************C
C                                                                           C
C     THIS FUNCTION SUBPROGRAM PROVIDES THE RATE COEFFICIENT FOR            C
C     NITRIFICATION  AS    A FUNCTION OF SOIL WATER SUCTION FOR             C
C     INDIFIDUAL SOIL LAYERS (SEE TEXT ).  THE USER MAY INCORPORATE OTHER   C
C     VARIABLES, I. E. TIME, SOIL DEPTH, ETC., AS DESIRED.                  C
C     ***********************************************************************
C
      FUNCTION ZZ1(M,HH,WC)
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L9/   TIME,TINF,TCYC
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L16/  REX1,RNIT1,RDNIT1
      COMMON/L17/  REX2,RNIT2,RDNIT2
      COMMON/L18/  REX3,RNIT3,RDNIT3
      ZZ1=0.0
      WH=-HH
      IF(WH.GT.15000) RETURN
      Z=M*DZ
      IF(Z.GT.CL2)  GO TO 10
      IF(Z.GT.CL1)  GO TO 5
      RK1=RNIT1
      GO TO 15
    5 CONTINUE
      RK1=RNIT2
      GO TO 15
   10 CONTINUE
      RK1=RNIT3
   15 CONTINUE
      IF(WH.GT.10.0) GO TO 1
      RETURN
    1 IF(WH.GT.50.0)  GO TO 2
      ZZ1=RK1*(WH-10.0)*0.0050
      RETURN
    2 IF(WH.GT.100.0) GO TO 3
      ZZ1=RK1*(0.200+(WH-50.0)*0.0060)
      RETURN
    3 IF(WH.GT.433.0) GO TO 4
      ZZ1=RK1*(0.500+(WH-100.0)*0.00150)
      RETURN
    4 ZZ1=RK1*(1.000-(WH-433.0)*0.00020)
      IF(WH.GT.1000.0) ZZ1=RK1*(0.950-0.050*WH/1000.0)
      RETURN
      END
```

```
C**********************************************************************C
C                                                                      C
C      D E N I T R I F I C A T I O N    R A T E    P R O G R A M      C
C                                                                      C
C**********************************************************************C
C                                                                      C
C     THIS FUNCTION SUBPROGRAM PROVIDES THE RATE COEFFICIENT FOR       C
C     DENITRIFICATION   AS A FUNCTION OF SOIL WATER CONTENT  FOR      C
C     INDIFIDUAL SOIL LAYERS (SEE TEXT ).  THE USER MAY INCORPORATE OTHER C
C     VARIABLES, I. E. TIME, SOIL DEPTH, ETC., AS DESIRED.             C
C**********************************************************************C
C
      FUNCTION ZZ2(M,HH,WC)
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L9/   TIME,TINF,ICYC
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L15/  ROU1,THS1,ROU2,THS2,ROU3,THS3
      COMMON/L16/  REX1,RNIT1,RDNIT1
      COMMON/L17/  REX2,RNIT2,RDNIT2
      COMMON/L18/  REX3,RNIT3,RDNIT3
      ZZ2=0.0
      Z=M*DZ
      IF(Z.GT.CL2)  GO TO 10
      IF(Z.GT.CL1)  GO TO 5
      RK2=RDIN1
      WSAT=THS1
      GO TO 15
  5   RK2=RDIN2
      WSAT=THS2
      GO TO 15
 10   RK2=RDIN3
      WSAT=THS3
 15   CONTINUE
      IF((WC/WSAT).LT.0.80) RETURN
      ZZ2=RK2*(WC-0.80*WSAT)/(0.10*WSAT)
      IF(WC.GE.(0.90*WSAT)) ZZ2=RK2
      RETURN
      END
```

```
C      ************************************************************************
C                                                                             C
C      A M M O N I U M    E X C H A N G E     P R O G R A M
C                                                                             C
C*****************************************************************************C
C      THIS FUNCTION SUBPROGRAM PROVIDES THE RETARDATION FACTOR               C
C      FOR AMMONIUM EXCHANGE, WHERE R IS A FUNCTION OF SOIL WATER CONTENT AND C
C      BULK DENSITY OF INDIVIDUAL SOIL LAYERS.                                C
C*****************************************************************************C
C                                                                             C
       FUNCTION ZZ3(M,HH,WC)
       COMMON/L4/    ALPHA,BETA,DT,DZ
       COMMON/L9/    TIME,TINF,TCYC
       COMMON/L11/   CL,CL1,CL2,L1,L2
       COMMON/L15/   ROU1,THS1,ROU2,THS2,ROU3,THS3
       COMMON/L16/   REX1,RNIT1,RDNIT1
       COMMON/L17/   REX2,RNIT2,RDNIT2
       COMMON/L18/   REX3,RNIT3,RDNIT3
       Z=M*DZ
       IF(Z.GT.CL2)  GO TO 10
       IF(Z.GT.CL1)  GO TO 5
       ZZ3=1.0+REX1*ROU1/WC
       RETURN
  5    ZZ3=1.0+REX2*ROU2/WC
       RETURN
  10   ZZ3=1.0+REX3*ROU3/WC
       RETURN
       END
```

```
C***********************************************************************C
C     A M M O N I U M   T R A N S P O R T  &  T R A N S F O R M O T I O N S   C
C                                                                       C
C                            P R O G R A M                              C
C                                                                       C
C***********************************************************************C
C                                                                       C
C     THIS SUBROUTINE PROVIDES THE SOLUTION TO THE AMMONIUM TRANSPORT   C
C     AND TRANSFORMATION EQUATION UNDER TRANSIENT FLOW CONDITIONS.      C
C     IT ALSO CALCULATES THE AMMONIUM UPTAKE BY PLANT ROOTS. THE        C
C     METHOD OF SOLUTION IS THE FINITE DIFFERENCE APPROXIMATION METHOD. C
C     ( SEE TEXT ).                                                     C
C     THE RATE OF NITRIFICATION , DENITRIFICATION AND THE DISTRIBUTION  C
C     COEFFICIENT FOR NH4-N EXCHANGE ARE OBTAINED FROM FUNCTIONS        C
C     ZZ1, ZZ2,  AND ZZ3 ,  RESPECTIVELY.                               C
C***********************************************************************C
C
      SUBROUTINE AMONIA
C     NH-4  PRGRAM
      COMMON/L1/   C(310),Y(310)
      COMMON/L2/   AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L5/   NX,NX1,NEMAX,CON1
      COMMON/L6/   PLNH4,PLNO3,DNITRF
      COMMON/L7/   SFLUX,ET,CM,CK,CSNH4,CSNO3,DISP,XL
      COMMON/L9/   TIME,TINF,TCYC
      COMMON/L10/  H(310),CON(310),CAP(310),TH(310)
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L15/  ROU1,THS1,ROU2,THS2,ROU3,THS3
      COMMON/L16/  REX1,RNIT1,RDNIT1
      COMMON/L17/  REX2,RNIT2,RDNIT2
      COMMON/L18/  REX3,RNIT3,RDNIT3
      M=1
      WFLX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      SSINF=WFLX
      FF=DZ*2.0
      C(1)=(SSINF*FF*CSNH4+DISP*TH(1)*C(3)/2)/(SSINF*FF+DISP*TH(1)/2)
      IF(SFLUX.LE.0.0) GO TO 13
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
C
      DO  5  I=1,NM1
      RKK=ZZ3(M,H(M),TH(M))
      AA(I)=RKK+2.0*ALPHA*DISP-BETA*VPP/TH(M)
      BB(I)=BETA*VPP/TH(M)-ALPHA*DISP
      R(I)=RKK*C(M)+ALPHA*DISP*(C(M+1)-2.0*C(M)+C(M-1))
      RK1=ZZ1(M,H(M),TH(M))
      R(I)=R(I)-DT*RK1*C(M)
      M=I+2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      CC(I)=-ALPHA*DISP
    5 CONTINUE
      M=N
      RKK=ZZ3(M,H(M),TH(M))
      AA(NM1)=RKK+ALPHA*DISP
      R(1)=R(1)+ALPHA*DISP*C(1)
```

```
      X1=0.0
      DO  6  I=1,NX1
      PN=QN*RDIST(I+1)*C(I+1)/(QK+C(I+1)+Y(I+1))
      X1=X1+DT*PN
    6 R(I)=R(I)-DT*PN/TH(I+1)
      PLNH4=PLNH4+X1*DZ
      GO TO 14
C
   13 CONTINUE
      C(1)=C(2)
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      DO  11 I=1,NM1
      RKK=ZZ3(M,H(M),TH(M))
      AA(I)=RKK+2.0*ALPHA*DISP-BETA*VPP/TH(M)
      BB(I)=BETA*VPP/TH(M)-ALPHA*DISP
      R(I)=RKK*C(M)+ALPHA*DISP*(C(M+1)-2.0*C(M)+C(M-1))
      RK1=ZZ1(M,H(M),TH(M))
      R(I)=R(I)-DT*RK1*C(M)
      M=I+2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      CC(I)=-ALPHA*DISP
   11 CONTINUE
      M=N
      RKK=ZZ3(M,H(M),TH(M))
      AA(NM1)=RKK+ALPHA*DISP
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      RKK=ZZ3(M,H(M),TH(M))
      AA(1)=RKK+ALPHA*DISP-BETA*VPP/TH(M)
C
      X1=0.0
      DO  7  I=1,NX1
      PN=QN*RDIST(I+1)*C(I+1)/(QK+C(I+1)+Y(I+1))
      X1=X1+DT*PN
    7 R(I)=R(I)-DT*PN/TH(I+1)
      PLNH4=PLNH4+X1*DZ
   14 CONTINUE
      CALL TRIDM(AA,BB,CC,R,NM1)
      DO  15  I=2,N
   15 C(I)=R(I-1)
      C(NP1)=C(N)
      RETURN
      END
```

```
C
C**********************************************************************C
C                                                                      C
C     N I T R A T E   T R A N S P O R T  &  T R A N S F O R M O T I O S   C
C                                                                      C
C                           P R O G R A M                              C
C                                                                      C
C**********************************************************************C
C                                                                      C
C     THIS SUBROUTINE PROVIDES THE SOLUTION TO THE  NITRATE TRANSPORT  C
C     AND TRANSFORMATION EQUATION UNDER TRANSIENT FLOW CONDITIONS.     C
C     IT ALSO CALCULATES THE  NITRATE UPTAKE BY PLANT ROOTS.   THE     C
C     METHOD OF SOLUTION IS THE FINITE DIFFERENCE APPROXIMATION METHOD.C
C     ( SEE TEXT ).                                                    C
C     THE RATE OF NITRIFICATION , DENITRIFICATION AND THE DISTRIBUTION C
C     COEFFICIENT FOR NH4-N EXCHANGE ARE OBTAINED FROM FUNCTIONS       C
C     ZZ1, ZZ2,  AND ZZ3 ,  RESPECTIVELY.                              C
C**********************************************************************C
C
      SUBROUTINE NITRAT
C     NO3- PROGRAM
      COMMON/L1/   C(310),Y(310)
      COMMON/L2/   AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L5/   NX,NX1,NRMAX,CON1
      COMMON/L6/   PLNH4,PLNO3,DNITRF
      COMMON/L7/   SFLUX,ET,QM,QK,CSNH4,CSNO3,DISP,XL
      COMMON/L9/   TIME,TINF,TCYC
      COMMON/L10/  H(310),CON(310),CAP(310),TH(310)
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L15/  ROU1,THS1,ROU2,THS2,ROU3,THS3
      COMMON/L16/  REX1,RNIT1,RDNIT1
      COMMON/L18/  REX3,RNIT3,RDNIT3
      M=1
      WFLX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      SSINF=WFLX
      FF=DZ*2.0
      Y(1)=(SSINF*FF*CSNO3+DISP*TH(1)*Y(3)/2)/(SSINF*FF+DISP*TH(1)/2)
      IF(SFLUX.LE.0.0) GO TO 13
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
C
      X2=0.0
C
      DO  5  I=1,NM1
      AA(I)=1.0+2.0*ALPHA*DISP-BETA*VPP/TH(M)
      BB(I)=BETA*VPP/TH(M)-ALPHA*DISP
      R(I)=Y(M)+ALPHA*DISP*(Y(M+1)-2.0*Y(M)+Y(M-1))
      RK1=ZZ1(M,H(M),TH(M))
      RK2=ZZ2(M,H(M),TH(M))
      R(I)=R(I)+DT*RK1*C(M)-DT*RK2*Y(M)
      X2=X2+DT*RK2*TH(I)*Y(I)
      M=I+2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      CC(I)=-ALPHA*DISP
    5 CONTINUE
      DNITRF=DNITRF+X2*DZ
```

```
      M=N
      AA(NM1)=1.0+ALPHA*DISP
      R(1)=R(1)+ALPHA*DISP*Y(1)
C
      X1=0.0
      DO 6 I=1,NX1
      PN=QM*RDIST(I+1)*Y(I+1)/(QK+C(I+1)+Y(I+1))
      X1=X1+DT*PN
    6 R(I)=R(I)-DT*PN/TH(I+1)
      PLNO3=PLNO3+X1*DZ
      GO TO 14
C
   13 CONTINUE
      Y(1)=Y(2)
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
C
      X2=0.0
C
      DO 11 I=1,NM1
      AA(I)=1.0+2.0*ALPHA*DISP-BETA*VPP/TH(M)
      BB(I)=BETA*VPP/TH(M)-ALPHA*DISP
      R(I)=Y(M)+ALPHA*DISP*(Y(M+1)-2.0*Y(M)+Y(M-1))
      RK1=ZZ1(M,H(M),TH(M))
      RK2=ZZ2(M,H(M),TH(M))
      R(I)=R(I)+DT*RK1*C(M)-DT*RK2*Y(M)
      X2=X2+DT*RK2*TH(I)*Y(I)
      M=I+2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      CC(I)=-ALPHA*DISP
   11 CONTINUE
      DNITRF=DNITRF+X2*DZ
      M=N
      AA(NM1)=1.0+ALPHA*DISP
      M=2
      VPP=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
      AA(1)=1.0+ALPHA*DISP-BETA*VPP/TH(M)
C
      X1=0.0
      DO 7 I=1,NX1
      PN=QM*RDIST(I+1)*Y(I+1)/(QK+C(I+1)+Y(I+1))
      X1=X1+DT*PN
    7 R(I)=R(I)-DT*PN/TH(I+1)
      PLNO3=PLNO3+X1*DZ
   14 CONTINUE
      CALL TRIDM(AA,BB,CC,R,NM1)
      DO 15 I=2,N
   15 Y(I)=R(I-1)
      Y(NP1)=Y(N)
      RETURN
      END
```

```
C***************************************************************************C
C                                                                           C
C                    P R O G R A M   O U T P U T                            C
C                                                                           C
C***************************************************************************C
C                                                                           C
C          THE FUNCTION OF THIS PROGRAM ID TO PRINT THE RESULTS FROM        C
C      MODEL PREDICTION AT SPECIFIED TIMES.   IN ADDITION IT CALCULATES     C
C      THE TOTAL AMOUNTS OF NITROGEN IN THE SOIL SYSTEM AND THAT TAKEN      C
C      UP BY THE PLANTS                                                     C
C***************************************************************************C
C
C
      SUBROUTINE OUTPUT
      COMMON/L1/   C(310),Y(310)
      COMMON/L2/   AA(310),BB(310),CC(310),R(310),RDIST(310)
      COMMON/L3/   N,NM1,NM2,NP1,NP2
      COMMON/L4/   ALPHA,BETA,DT,DZ
      COMMON/L5/   NX,NX1,NRMAX,CON1
      COMMON/L6/   PLNH4,PLNO3,DNITRF
      COMMON/L7/   SFLUX,ET,QM,CK,CSNH4,CSNO3,DISP,XL
      COMMON/L8/   XXX(30),C1(30),C2(30),C3(30),C4(30)
      COMMON/L9/   TIME,TINF,TCYC
      COMMON/L10/  H(310),CON(310),CAP(310),TH(310)
      COMMON/L11/  CL,CL1,CL2,L1,L2
      COMMON/L15/  ROU1,THS1,ROU2,THS2,ROU3,THS3
      COMMON/L16/  REX1,RNIT1,RDNIT1
      COMMON/L17/  REX2,RNIT2,RDNIT2
      COMMON/L18/  REX3,RNIT3,RDNIT3
 100  FORMAT('1')
 200  FORMAT('1',40X,'TIME , DAYS =',F10.2/)
 299  FORMAT(T10,'SOIL DEPTH',
     $T25,'PRESSURE HEAD',
     $T43,'SOIL-WATER CONTENT',
     *T65,'WATER FLOW',
     *T80,'AMMONIUM CONCENTRATION',
     $T107,'NITRATE CONCENTRATION')
 301  FORMAT(T14,'CM',T31,'CM',T46,'CM**3/CM**3',T66,'VELOCITY',T82,
     *'IN SOIL SOLUTION',T109,'IN SOIL SOLUTION')
 302  FORMAT(T68,'CM/HR',T82,'MICROGRAMS-N/ML',T109,'MICROGRAMS-N /ML'/)
 499  FORMAT(T10,F8.2,T24,F10.2,T45,F8.2,T65,F8.4,T86,F8.3,T112,F8.3)
 300  FORMAT(25X////,
     *25X,'TOTAL NO-3 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS =',
     $F10.3//,
     *25X,'TOTAL NH-4 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS =',
     $F10.3//,
     *25X,'TOTAL NH-4 NITROGEN IN  EXCHANGEABLE PHASE , MICROGRAMS =',
     $F10.3//,
     *25X,'TOTAL NH-4 NITROGEN IN  THE SOIL  PROFILE  , MICROGRAMS =',
     $F10.3//)
 600  FORMAT(25X,'TOTAL NITROGEN DENITRIFIED , MICROGRAMS  =',F10.3//)
  500 FORMAT(/,
     *25X,'TOTAL  NITRATE  NITROGEN UPTAKE,  MICROGRAMS =',F10.3//,
     *25X,'TOTAL  AMMONIUM NITROGEN UPTAKE,  MICROGRAMS =',F10.3//)
C
      WRITE(6,100)
      TIMM=TIME/24.0
      WRITE(6,200) TIMM
```

```
      WRITE(6,299)
      WRITE(6,301)
      WRITE(6,302)
      WFLX=SFLUX
      DO  20  I=1,NP1,2
      ZZ=(I-1)*DZ
      WRITE(6,499) ZZ,H(I),TH(I),WFLX,C(I),Y(I)
      WFLX=-CON(I)*(H(I+1)-H(I))/DZ+CON(I)
   20 CONTINUE
      M=NP1
      DO  30  I=1,M
      AA(I)=TH(I)*C(I)
   30 BB(I)=TH(I)*Y(I)
      CALL QSF(DZ,AA,R,M)
      XNH4=R(M)
      CALL QSF(DZ,BB,R,M)
      XNO3=R(M)
      CALL QSF(DZ,C,R,NP1)
      XT=R(NP1)
      CALL QSF(DZ,C,R,L1)
      X1=R(L1)
      CALL QSF(DZ,C,R,L2)
      X12=R(L2)
      X2=X12-X1
      X3=XT-X12
      ENH4=X1*ROU1*REX1+X2*ROU2*REX2+X3*ROU3*REX3
      XTNH4=XNH4+ENH4
      WRITE(6,300)  XNO3,XNH4,ENH4,XTNH4
      WRITE(6,600)  DNITRF
C
      WRITE(6,500)  PLNO3,PLNH4
      RETURN
      END

C
C
C*****************************************************************************C
C                                                                             C
C     T R I D I A G O N A L    M A T R I X    P R O G R A M
C                                                                             C
C*****************************************************************************C
C                                                                             C
C     THIS SUBROUTINE PROVIDES SOLUTION TO THE TRIDIAGONAL MATRIX -          C
C     VECTOR EQUATIONS FOR  SUBROUTINE WATER, AMONIA, AND NITRAT             C
C                                                                             C
C*****************************************************************************C
C
      SUBROUTINE THIDM(A,B,C,D,N)
      DIMENSION A(1),B(1),C(1),D(1)
      DO  1  I=2,N
      C(I-1)=C(I-1)/A(I-1)
      A(I)=A(I)-(C(I-1)*B(I-1))
    1 CONTINUE
      DO  2  I=2,N
      D(I)=D(I)-(C(I-1)*D(I-1))
    2 CONTINUE
      D(N)=D(N)/A(N)
      DO  3  I=2,N
      D(N+1-I)=(D(N+1-I)-(B(N+1-I)*D(N+2-I)))/A(N+1-I)
    3 CONTINUE
      RETURN
      END
```

APPENDIX B: EXAMPLE OF INPUT AND OUTPUT

```
                    I N P U T   D A T A

INITIAL DT, HR =    0.01000
INITIAL DZ  , CM=   1.00000

FLUX OF WASTE WATER APPLICATION,  CM/ HR =    0.50000
EVAPOTRANSPIRATION RATE, CM/HR =    0.01000
NITROGEN UPTAKE RATE, MICROGRAM-N/CM OF ROOT LENGTH PER HOUR =    0.00100
MICHAELIS CONSTANT =     1.00000
CONCENTRATION OF APPLIED NH4-N , MG/LITRE =  25.00000
CONCENTRATION OF APPLIED NO3-N , MG/LITRE =   0.0
SOLUTE DISPERSION COEFFICIENT, CM**2/HR =    2.50000

TOTAL LENGTH OF SOIL PROFILE, CM = 150.00000
SOIL DEPTH TO THE FIRST SOIL LAYER, CM =  15.00000
SOIL DEPTH TO THE SECOND SOIL LAYER, CM =  45.00000

SOIL WATER PARAMETERS FOR THE FIRST  LAYER :     0.9600E-05     0.2763E+02     0.1000E+03     0.1000E+01
SOIL WATER PARAMETERS FOR THE SECOND LAYER :     0.2200E-05     0.3070E+02     0.4000E+02     0.1000E+01
SOIL WATER PARAMETERS FOR THE THIRD  LAYER :     0.2100E-05     0.3887E+02     0.3000E+02     0.1000E+01
FIRST LAYER  ;  BULK DENSITY =    1.41000         SATURATION =   0.44000
SECOND LAYER ;  BULK DENSITY =    1.59000         SATURATION =   0.42000
THIRD  LAYER ;  BULK DENSITY =    1.55000         SATURATION =   0.34000

FIRST LAYER:            NH4-N EXCHANGEABLE COEFFICIENT, CM3/GM =    0.25000
                       NITRIFICATION RATE COEF.,HR-1 =    0.10000
                       DENITRIFICATION RATE COEF., HR-1 =    0.01000
SECOND LAYER            NH4-N EXCHANGEABLE COEFFICIENT, CM3/GM =    0.25000
                       NITRIFICATION RATE COEF.,HR-1 =    0.10000
                       DENITRIFICATION RATE COEF., HR-1 =    0.01000
THIRD LAYER:            NH4-N EXCHANGEABLE COEFFICIENT, CM3/GM =    0.25000
                       NITRIFICATION RATE COEF.,HR-1 =    0.10000
                       DENITRIFICATION RATE COEF., HR-1 =    0.01000
DURATION OF WASTE WATER APPLICATION , HRS =  10.00000
SCHEDULE OF WASTE WATER APPLICATION, I.E. CYCLE DURATION = 168.00000
NUMBER OF CYCLES =   1

TIME AT WHICH OUTPUT DATA IS REQUESTED,HR =  24.00000
```

TIME , DAYS = 0.0

SOIL DEPTH CM	PRESSURE HEAD CM	SOIL-WATER CONTENT CM**3/CM**3	WATER FLOW VELOCITY CM/HR	AMMONIUM CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N/ML	NITRATE CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N /ML
0.0	-50.00	0.29	0.5000	25.000	0.0
2.00	-48.13	0.30	0.0000	22.467	1.867
4.00	-46.27	0.30	0.0000	19.933	3.733
6.00	-44.40	0.30	0.0000	17.400	5.600
8.00	-42.53	0.31	0.0000	14.867	7.467
10.00	-40.67	0.31	0.0000	12.333	9.333
12.00	-38.80	0.32	0.0000	9.800	11.200
14.00	-36.93	0.32	0.0001	7.267	13.067
16.00	-37.80	0.22	0.0046	5.833	13.800
18.00	-41.40	0.21	0.0002	5.500	13.400
20.00	-45.00	0.20	0.0001	5.167	13.000
22.00	-48.60	0.19	0.0001	4.833	12.600
24.00	-52.20	0.18	0.0001	4.500	12.200
26.00	-55.80	0.18	0.0001	4.167	11.800
28.00	-59.40	0.17	0.0001	3.833	11.400
30.00	-63.00	0.16	0.0001	3.500	11.000
32.00	-66.60	0.16	0.0001	3.167	10.600
34.00	-70.20	0.15	0.0001	2.833	10.200
36.00	-73.80	0.15	0.0001	2.500	9.800
38.00	-77.40	0.14	0.0001	2.167	9.400
40.00	-81.00	0.14	0.0001	1.833	9.000
42.00	-84.60	0.13	0.0001	1.500	8.600
44.00	-88.20	0.13	0.0000	1.167	8.200
46.00	-89.14	0.09	0.0003	0.990	7.924
48.00	-87.43	0.09	0.0000	0.971	7.771
50.00	-85.71	0.09	0.0000	0.952	7.619
52.00	-84.00	0.09	0.0000	0.933	7.467
54.00	-82.29	0.09	0.0000	0.914	7.314
56.00	-80.57	0.09	0.0000	0.895	7.162
58.00	-78.86	0.09	0.0000	0.876	7.010
60.00	-77.14	0.10	0.0000	0.857	6.857
62.00	-75.43	0.10	0.0000	0.838	6.705
64.00	-73.71	0.10	0.0000	0.819	6.552
66.00	-72.00	0.10	0.0000	0.800	6.400
68.00	-70.29	0.10	0.0000	0.781	6.248
70.00	-68.57	0.10	0.0000	0.762	6.095
72.00	-66.86	0.11	0.0000	0.743	5.943
74.00	-65.14	0.11	0.0000	0.724	5.790
76.00	-63.43	0.11	0.0000	0.705	5.638
78.00	-61.71	0.11	0.0000	0.686	5.486
80.00	-60.00	0.11	0.0000	0.667	5.333
82.00	-58.29	0.12	0.0000	0.648	5.181
84.00	-56.57	0.12	0.0000	0.629	5.029
86.00	-54.86	0.12	0.0000	0.610	4.876
88.00	-53.14	0.12	0.0000	0.590	4.724
90.00	-51.43	0.13	0.0000	0.571	4.571
92.00	-49.71	0.13	0.0000	0.552	4.419
94.00	-48.00	0.13	0.0000	0.533	4.267
96.00	-46.29	0.13	0.0000	0.514	4.114
98.00	-44.57	0.14	0.0000	0.495	3.962
100.00	-42.86	0.14	0.0000	0.476	3.810
102.00	-41.14	0.14	0.0000	0.457	3.657
104.00	-39.43	0.15	0.0000	0.438	3.505
106.00	-37.71	0.15	0.0000	0.419	3.352
108.00	-36.00	0.15	0.0000	0.400	3.200

110.00	-34.33	0.16	0.0001	0.365	3.119
112.00	-32.63	0.16	0.0002	0.348	2.956
114.00	-30.93	0.17	0.0002	0.330	2.794
116.00	-29.24	0.17	0.0002	0.312	2.634
118.00	-27.55	0.18	0.0003	0.295	2.475
120.00	-25.88	0.18	0.0004	0.277	2.318
122.00	-24.23	0.19	0.0005	0.259	2.161
124.00	-22.61	0.19	0.0006	0.242	2.006
126.00	-21.02	0.20	0.0008	0.224	1.852
128.00	-19.47	0.21	0.0012	0.206	1.698
130.00	-17.94	0.21	0.0016	0.188	1.546
132.00	-16.40	0.22	0.0021	0.170	1.396
134.00	-14.83	0.23	0.0026	0.151	1.249
136.00	-13.19	0.24	0.0030	0.133	1.106
138.00	-11.48	0.25	0.0034	0.115	0.970
140.00	-9.69	0.26	0.0038	0.097	0.844
142.00	-7.83	0.27	0.0040	0.080	0.732
144.00	-5.92	0.28	0.0041	0.065	0.640
146.00	-3.96	0.30	0.0042	0.054	0.572
148.00	-1.99	0.32	0.0043	0.047	0.533
150.00	-0.00	0.34	0.0043	0.045	0.524

TOTAL NO-3 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS = 145.575

TOTAL NH-4 NITROGEN IN SOIL SOLUTION PHASE , MICROGRAMS = 143.187

TOTAL NH-4 NITROGEN IN EXCHANGEABLE PHASE , MICROGRAMS = 168.121

TOTAL NH-4 NITROGEN IN THE SOIL PROFILE , MICROGRAMS = 311.308

TOTAL NITROGEN DENITRIFIED , MICROGRAMS = 0.0

TOTAL NITRATE NITROGEN UPTAKE, MICROGRAMS = 11.072

TOTAL AMMONIUM NITROGEN UPTAKE, MICROGRAMS = 37.800

TIME , DAYS = 1.00

SOIL DEPTH CM	PRESSURE HEAD CM	SOIL-WATER CONTENT CM**3/CM**3	WATER FLOW VELOCITY CM/HR	AMMONIUM CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N/ML	NITRATE CONCENTRATION IN SOIL SOLUTION MICROGRAMS-N /ML
0.0	-30.20	0.34	0.0	18.575	2.351
2.00	-28.27	0.34	0.0049	18.515	2.378
4.00	-26.33	0.35	0.0036	18.327	2.448
6.00	-24.39	0.35	0.0049	17.874	2.586
8.00	-22.47	0.36	0.0063	17.121	2.805
10.00	-20.54	0.37	0.0078	16.081	3.112
12.00	-18.62	0.37	0.0094	14.805	3.513
14.00	-16.70	0.38	0.0111	13.361	4.000
16.00	-14.82	0.31	0.0129	11.849	4.568
18.00	-14.05	0.31	0.0167	10.355	5.213
20.00	-13.40	0.31	0.0212	8.950	5.908
22.00	-12.87	0.32	0.0256	7.682	6.622
24.00	-12.42	0.32	0.0301	6.577	7.321
26.00	-12.07	0.32	0.0345	5.635	7.973
28.00	-11.82	0.32	0.0388	4.843	8.549
30.00	-11.68	0.33	0.0431	4.174	9.028
32.00	-11.70	0.33	0.0472	3.600	9.393
34.00	-11.92	0.32	0.0511	3.094	9.639
36.00	-12.46	0.32	0.0547	2.635	9.765
38.00	-13.57	0.31	0.0575	2.213	9.781
40.00	-15.83	0.30	0.0591	1.825	9.700
42.00	-21.34	0.27	0.0581	1.477	9.541
44.00	-54.45	0.18	0.0494	1.188	9.328
46.00	-88.21	0.09	0.0157	1.003	9.079
48.00	-87.11	0.09	0.0000	0.901	8.817
50.00	-85.55	0.09	0.0000	0.839	8.563
52.00	-83.86	0.09	0.0000	0.802	8.322
54.00	-82.15	0.09	0.0000	0.779	8.097
56.00	-80.44	0.09	0.0000	0.763	7.888
58.00	-78.73	0.09	0.0000	0.750	7.691
60.00	-77.03	0.10	0.0000	0.739	7.505
62.00	-75.32	0.10	0.0000	0.726	7.322
64.00	-73.62	0.10	0.0000	0.714	7.139
66.00	-71.92	0.10	0.0000	0.701	6.956
68.00	-70.21	0.10	0.0000	0.688	6.774
70.00	-68.50	0.10	0.0000	0.675	6.592
72.00	-66.79	0.11	0.0000	0.661	6.410
74.00	-65.08	0.11	0.0000	0.647	6.229
76.00	-63.37	0.11	0.0000	0.633	6.048
78.00	-61.66	0.11	0.0000	0.619	5.869
80.00	-59.96	0.11	0.0000	0.605	5.691
82.00	-58.25	0.12	0.0000	0.591	5.514
84.00	-56.54	0.12	0.0000	0.576	5.338
86.00	-54.83	0.12	0.0000	0.561	5.163
88.00	-53.12	0.12	0.0000	0.546	4.990
90.00	-51.41	0.13	0.0000	0.531	4.818
92.00	-49.70	0.13	0.0000	0.516	4.646
94.00	-47.99	0.13	0.0000	0.500	4.475
96.00	-46.28	0.13	0.0001	0.484	4.304
98.00	-44.57	0.14	0.0001	0.468	4.134
100.00	-42.86	0.14	0.0001	0.452	3.963
102.00	-41.15	0.14	0.0001	0.435	3.792
104.00	-39.45	0.15	0.0001	0.418	3.622
106.00	-37.74	0.15	0.0001	0.400	3.453
108.00	-36.03	0.15	0.0001	0.383	3.285

110.00	-34.33	0.16	0.0001	0.365	3.119
112.00	-32.63	0.16	0.0002	0.348	2.956
114.00	-30.93	0.17	0.0002	0.330	2.794
116.00	-29.24	0.17	0.0002	0.312	2.634
118.00	-27.55	0.18	0.0003	0.295	2.475
120.00	-25.88	0.18	0.0004	0.277	2.318
122.00	-24.23	0.19	0.0005	0.259	2.161
124.00	-22.61	0.19	0.0006	0.242	2.006
126.00	-21.02	0.20	0.0008	0.224	1.852
128.00	-19.47	0.21	0.0012	0.206	1.698
130.00	-17.94	0.21	0.0016	0.188	1.546
132.00	-16.40	0.22	0.0021	0.170	1.396
134.00	-14.83	0.23	0.0026	0.151	1.249
136.00	-13.19	0.24	0.0030	0.133	1.106
138.00	-11.48	0.25	0.0034	0.115	0.970
140.00	-9.69	0.26	0.0038	0.097	0.844
142.00	-7.83	0.27	0.0040	0.080	0.732
144.00	-5.92	0.28	0.0041	0.065	0.640
146.00	-3.96	0.30	0.0042	0.054	0.572
148.00	-1.99	0.32	0.0043	0.047	0.533
150.00	-0.00	0.34	0.0043	0.045	0.524

TOTAL NO-3 NITROGEN IN SOIL SOLUTION PHASE . MICROGRAMS = 145.575

TOTAL NH-4 NITROGEN IN SOIL SOLUTION PHASE . MICROGRAMS = 143.187

TOTAL NH-4 NITROGEN IN EXCHANGEABLE PHASE . MICROGRAMS = 168.121

TOTAL NH-4 NITROGEN IN THE SOIL PROFILE . MICROGRAMS = 311.308

TOTAL NITROGEN DENITRIFIED . MICROGRAMS = 0.0

TOTAL NITRATE NITROGEN UPTAKE. MICROGRAMS = 11.072

TOTAL AMMONIUM NITROGEN UPTAKE. MICROGRAMS = 37.800

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Selim, H.M.

Simplified model for prediction of nitrogen behavior in land treatment of wastewater / by H.M. Selim and I.K. Iskandar. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1980.

iv, 53 p., illus.; 28 cm. (CRREL Report 80-12.)

Prepared for Directorate of Civil Works - Office, Chief of Engineers by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory.

Bibliography: p. 20.

1. Land treatment. 2. Models. 3. Nitrogen cycle. 4. Wastewater treatment. I. I.K. Iskandar, co-author. II. United States. Army. Corps of Engineers. III. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. IV. Series: CRREL Report 80-12.